THE
PHYSIOLOGY OF VISION.

THE

PHYSIOLOGY

OF

VISION.

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IT IS THE BOAST OF SCIENCE TO HAVE BEEN ABLE TO TRACE SO FAR THE REFINED CONTRIVANCES OF THIS MOST ADMIRABLE ORGAN; NOT ITS SHAME TO FIND SOMETHING STILL CONCEALED FROM ITS SCRUTINY; FOR, HOWEVER ANATOMISTS MAY DIFFER ON POINTS OF STRUCTURE, OR PHYSIOLOGISTS DISPUTE ON MODES OF ACTION, THERE IS THAT IN WHAT WE *DO* UNDERSTAND OF THE FORMATION OF THE EYE SO SIMILAR, AND YET SO INFINITELY SUPERIOR, TO A PRODUCT OF HUMAN INGENUITY,—SUCH THOUGHT, SUCH CARE, SUCH REFINEMENT, SUCH ADVANTAGE TAKEN OF THE PROPERTIES OF NATURAL AGENTS USED AS MERE INSTRUMENTS, FOR ACCOMPLISHING A GIVEN END, AS FORCE UPON US A CONVICTION OF DELIBERATE CHOICE AND PREMEDITATED DESIGN, MORE STRONGLY, PERHAPS, THAN ANY SINGLE CONTRIVANCE TO BE FOUND, WHETHER IN ART OR NATURE, AND RENDER ITS STUDY AN OBJECT OF THE DEEPEST INTEREST.

J. F. W. HERSCHEL.

PREFACE.

The author of the following work has been engaged for more than twenty years in teaching the structure, functions, and diseases of the eye, to medical students. His course of lectures on these subjects being limited to a period of three months, or about sixty lectures, and intended chiefly as a practical course on a branch of the healing art, he has generally been obliged to curtail the very interesting matter of the physiology of vision, more especially of late years, in order that he might do that justice to the anatomical and pathological departments of his subject, which the previous studies of his auditors, their ultimate views in attending to the eye, and the continual improvements taking place in practical ophthalmology, seemed to him to demand. In order to supply in some measure the deficiency arising from this necessary abridgment, he has often been solicited to publish a short systematical work on the physiology of vision.

As it is now presented to his pupils and the public, the following treatise is one of very humble pretensions. Its chief claim to their indulgence is its being an attempt to explain perspicuously, and in accordance with scientific principles, one of the most interesting subjects of human inquiry, viz.

the laws of vision. The author is well aware that on such a subject, precise ideas only should be tolerated, and all vagueness rejected; but as unfortunately the study of mathematics is rarely made a preliminary to that of medicine, he has expressed himself as much as possible in common language, and, when mathematical truths were to be delivered, has in general adopted geometrical expressions, which, though more tedious and less elegant than analytical ones, may readily be understood even by those who are unacquainted with the elements of Euclid.

It is scarcely necessary to say, that there is little original in the following pages. All that the author has aimed at, has been to present a short and intelligible view of the labours of former inquirers. In doing so, he has availed himself of all the sources within his reach, of the number of which some notion may be formed from the references at the end of the chapters. To the writings of Porterfield, Young, Brewster, Biot, and Müller, he has been much indebted.

The range of subject embraced in the following pages has been confined by a constant reference to the fact, that they are intended chiefly for the use of those whose business it will be to distinguish and to treat the various diseases to which the eye is liable. At the same time, the author trusts that they will be found to contain such a view of this organ, as may interest also the general reader, for whose benefit he has made it his endeavour to combine the accuracy of a philosophical treatise with the facility of a popular work.

GLASGOW, 21*st April*, 1841.

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THE

PHYSIOLOGY OF VISION.

CHAPTER I.

INTRODUCTORY OBSERVATIONS.

§ 1. *Function of vision.*

PHYSIOLOGY is the science which explains the functions of the different parts of the living body.

The function of the eye is to distinguish colours; and by means of the colours reflected or emitted by surrounding objects, to enable us to recognise their presence, forms, sizes, positions, distances, and motions. The immediate instrument of visual perception, light, possessing a diversity of colours, and being presented to the eye in different degrees of intensity, produces particular impressions on the nerve of vision.

§ 2. *General account of the optic apparatus.*

The eyeball, the immediate organ of vision, is protected by the bones forming a cavity called the *orbit*. Within this cavity lies the cellular and fatty substance by which the eyeball is supported, and the muscles by which it is moved from side to side, or fixed upon the objects of perception. The blood-vessels which nourish the eyeball, and the nerves with

which its different parts are furnished, are also contained within the orbit.

The inside of the eyelids, and the anterior 5-12ths of the eyeball, are covered by a mucous membrane called the *tunica conjunctiva*, upon the exterior surface of which the tears are poured out from the lacrymal gland. The mucus of the conjunctiva serves to lubricate the parts, and render their motions easy; the tears wash away that mucus, as well as such foreign particles as may alight on the surface of the eye.

The eyelids, fringed with the eyelashes, and surmounted by the eyebrows, are opened and shut by particular muscular forces, and complete the parts destined to protect the eyeball —the *tutamina oculi.*

Although it is probable that none of its surfaces are truly spherical, the human eyeball is generally described as formed by two unequal spherical segments. The spheres to which these segments belong, would, if continued, touch each other internally at *c*, fig. 1. The one is part of a small sphere; and the other, part of a larger. The diameter of the larger sphere, 1, fig. 1. measures about 19-20ths, and that of the smaller sphere, 2, 13-20ths of an inch. The diameter of the base of the segment of the smaller sphere, *a b*, measures 9-20ths of an inch.

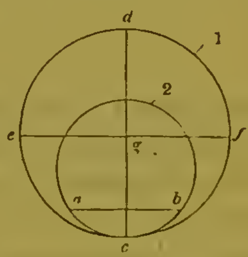

Fig. 1.

The external measurement of the axis of the eyeball, *c d*, fig. 2. is, in general, equal to its transverse diameter, *e f.* The eyeball, therefore, is spherical, except where the two segments of which it is composed are connected by a portion coincident with neither. The larger segment, or *sclerotica*, runs gradually into the smaller segment, or *cornea*; each suffers a slight alteration of form in being united, and thus an annular depression, *a b*, is created at their junction.

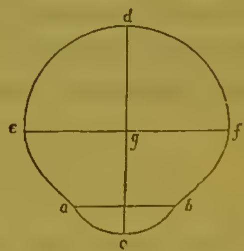

Fig. 2.

The eyeball consists of many parts, and these present a

variety of different textures. Its construction, generally considered, is that of several concentric spherical membranes, closely applied to one another, within which are contained certain transparent media, of different densities.

Its external shell is formed posteriorly by an opaque fibrous membrane, the *sclerotica*, 1, fig. 3. already referred to; while framed into the front of the eyeball is the transparent *cornea*, 2. In a horizontal section of the eyeball, such as is represented in fig. 3. 5-6ths of the circumference of the section are formed by the sclerotica, and the remaining 6th by the cornea.

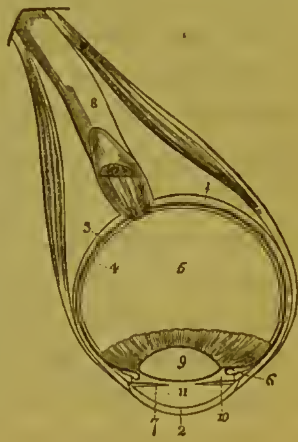

Fig. 3.

Within the sclerotica lies the *choroid coat*, 3, lined by a pigment of a dark brown colour.

While the greater part of the choroid invests the retina, 4, its anterior portion is in contact with the vitreous humour, 5. In a horizontal section, the portion in contact with the vitreous humour, and which receives the name of the *ciliary ring*, or *corpus ciliare*, measures about one-fifth of the whole. Around the crystalline body, the ciliary ring terminates in about seventy plaits or folds, 6, called the *ciliary processes*.

If we look through the cornea into the interior of the eye, we observe a membranous disc, called the *iris*, 7, nearly coinciding with the common base of the two segments of which the shell of the eye is formed. Nearly in its centre, the iris presents an aperture of variable diameter, known by the name of the *pupil*, contracting and expanding in the living subject, according to the brightness of the light, and the distance of the object to which the eye is directed. The anterior surface of the iris has a striated appearance, and is generally of a bluish or hazel colour; its posterior surface, like the internal surface of the choroid, is covered with dark-brown pigment.

Within the choroid, is the *retina*, 4, a transparent nervous membrane, extending from the optic nerve, 8, at the back of the eye, to within one-fourth of an inch of the circumference

of the crystalline lens, 9, and forming a cup, of which a horizontal section measures more than two-thirds of the circumference of a circle.

The globular space within the concavity of the retina is occupied by one of the transparent media of the eye, called the *vitreous humour*, 5. It is a fluid, so supported by a cellular structure as to present a gelatinous degree of consistence. Between the termination of the retina and the edge of the crystalline body, the vitreous humour is covered by the *ciliary ring* or *corpus ciliare* of the choroid, including the *ciliary processes*, already mentioned. This ring measures about one-fourth of an inch in breadth, but is somewhat broader on the temporal than on the nasal side of the eye.

Imbedded in the front of the vitreous humour, and close behind the pupil, lies the *crystalline lens*, 9, enclosed within a peculiar membrane or *capsule*.

The space between the crystalline and the cornea is occupied by a fluid called the *aqueous humour*. The iris, supported on both sides by this fluid, partially divides the cell in which it is contained into two compartments, known by the names of the *posterior*, 10, and *anterior*, 11, *chambers*, which communicate by the pupil.

Such is a general enumeration of the parts of which the eyeball consists. For an account of their structure and connexions, recourse must be had to books of anatomy.[1] In reference to their functions, the different parts of the eyeball may be arranged in four classes, viz. 1. The external shell, or consolidative coat,[2] formed by the sclerotica and cornea. 2. The dioptric parts, *i. e.* refractive media, or lenses; namely, the vitreous, crystalline, and aqueous humours, along with which must again be reckoned the cornea, as it performs a double office, serving at once as a lens and as portion of the consolidative coat of the eye. 3. Parts subsidiary to the perfection of the eye as an optical instrument; namely, the choroid, which serves to absorb the rays of light, and the iris, which is a diaphragm for obviating the spherical aberration of the lenses. 4. The specially sensitive parts; namely, the retina, and the extremity of the optic nerve, with which the retina is continuous.

The *optic nerve*, 8, quits the retina and the eye by an aperture in the posterior part of the choroid and sclerotica, not in the axis, but about one-fifth of an inch to the nasal side of the axis, and a little above the equator[3] of the eyeball. It passes back, through the orbit, and through a hole in the sphenoid bone, into the interior of the cranium. There, at the distance of about an inch and three quarters behind the eyeball, the nerve from the right eye meets with that from the left. The two nerves mingle, or partially decussate their fibres; then separate, proceed under the hemispheres of the cerebrum, traverse and adhere to the *crura cerebri*, embrace the tubercles called *corpora geniculata externa*, communicate with the *thalami nervorum opticorum*, and are supposed to end in the *corpora quadrigemina*, a little behind the middle of the brain.

§ 3. *Laws of light.*

It is unnecessary, on this occasion, to enter on any inquiry concerning the *nature* of light; for the theory of vision rests upon observations, totally independent of that question. So far as our subject is concerned, it matters not whether the change that occurs in space previous to the sensation of vision, be the progress of a succession of material particles, or of a vibratory movement of a line of other particles.

The facts upon which the theory of vision is founded are of so general an application, in regard to the phenomena of light, and the construction of optical instruments, that they are known by the name of the *laws of light*. They are principally these four:—

1. That from every luminous point, light tends to radiate in every direction, in straight lines.

2. That falling upon certain surfaces, light is reflected from them; and, in those cases, the angle of reflection is always equal to the angle of incidence.

3. That on passing obliquely out of one transparent medium into another of different density, light proceeds no longer in the same straight line, but is bent or refracted.

4. That light consists of differently coloured rays, possessing different degrees of refrangibility.

From these few principles, established by experience, a vast multitude of truths, equally certain with the principles themselves, and in fact, the whole theory of vision may be deduced by the mere application of mathematical reasoning. The first of the laws of light is the foundation of *optics proper*, or the theory of direct light; the second is the foundation of *catoptrics*, or the theory of reflected light; the third of *dioptrics*, or the theory of refracted light; and the fourth, of *chromatics*, or the theory of colours.

The above is the order in which the laws of light are commonly enumerated; but, from the eye being a dioptric instrument, and its catoptric effects being merely incidental, we shall find it more convenient to take them up in the order of 1, 3, 4, 2.

§ 4. *Explanation of terms.*

1. Any transparent body, through which light passes, as air, water, glass, &c. is called a *medium*. Even empty space is considered a medium.

2. The least portion of light, which emanates from a luminous body, is called a *ray*. Although a ray of light, regarded physically, is an infinitesimal pyramid, having for its vertex a luminous point, and for its base an infinitely small portion of any surface illuminated by it, rays are represented, for the sake of convenience, by mere mathematical lines, drawn in the directions in which the light is supposed to move.

3. A slender portion of rays, separated from the rest, is called a *pencil*, and a greater quantity, a *beam* of light.

4. Pencils of rays are generally of a conical form. Rays emanating from a point, as R, fig. 4, and receding from each

Fig. 4.

other as they advance, are called *diverging* rays; tending to a point, as F, fig. 5, at which they at last unite, or would

Fig. 5.

unite, if not prevented, they are styled *converging* rays.

Rays of light are naturally divergent, but they are made to converge artificially, by being reflected or refracted.

A pencil of *parallel* rays, fig. 6, consists in such as proceed

Fig. 6.

through all their course at equal distances from one another.

5. The point from which the rays of a pencil diverge, as R, fig. 4, or towards which they converge, as F, fig. 5, is called their *focus*[4] or *focal point.* Any point from which rays proceed is also called a *radiant* or *radiating point*, or simply a *radiant.*

The point from which rays are made apparently to diverge, or towards which they are made apparently to converge, by reflection or refraction, when in reality they diverge from or converge towards another point, is called a *virtual focus.*

The point to which parallel rays are reflected or refracted, receives the name of the *principal focus.*

The distance of the focus from the reflecting or refracting surface is called the *focal distance*, or *focal length.* This generally refers to the principal focus.

The focus before reflection or refraction is called the *focus of incident rays;* and the focus after reflection or refraction, the *focus of reflected* or *refracted rays.* Both together are called *conjugate foci;* and they are so related, that if either of them be the radiant point, or the focus of incident rays, the other will be the focus of reflected or refracted rays.

6. When a ray of light, falling or incident upon any surface,

is turned back into the medium in which it was moving, it is said to be *reflected.*

7. When a ray of light passes out of one medium into another, and has its direction changed at the common surface of the two media, it is said to be *refracted.*

8. The angle contained between the incident ray and a line drawn perpendicular to the reflecting or refracting surface, or to a plane touching that surface, at the point of incidence, is called the *angle of incidence.*

9. The angle contained between the reflected ray and the perpendicular to the reflecting surface at the point of incidence, is called the *angle of reflection.*

10. The angle contained between the refracted ray and the perpendicular to the refracting surface, at the point of incidence, is called the *angle of refraction.*

11. The angle contained between the incident ray produced and the reflected or refracted ray, is called the *angle of deviation.*

If S F fig. 7. represent a reflecting surface, A B a ray incident upon it, B C the reflected ray, and P R be drawn, through B, perpendicular to S F, and A B be produced to E; then, A B P is the angle of incidence, P B C the angle of reflection, and C B E the angle of deviation.

If S F be the surface of a refracting medium, A B the incident ray, and B D the refracted ray; then R B D is the angle of refraction, and E B D the angle of deviation.

§ 5. *General facts respecting reflection and refraction.*

1. The incident and the reflected ray lie always in the same plane; so do the incident and the refracted ray.[5]

2. All objects seen by reflection or refraction appear in that place or direction, from whence or in which the rays were last reflected or refracted to the eye. Thus, if the ray A B, fig. 7, proceed from an object at A to B, and be thence reflected to the eye of a spectator at C, the object will be seen not at A, but as if at G, in the direction of the reflected ray C B. And if the ray D B proceed from an object at D, and be refracted in

the direction B A to the eye of a spectator at A, the object will be seen not at D, but as if at E, in the direction of the refracted ray B A. Hence it is that objects are seen in mirrors, and that objects under water, if viewed obliquely, do not appear in their true places.

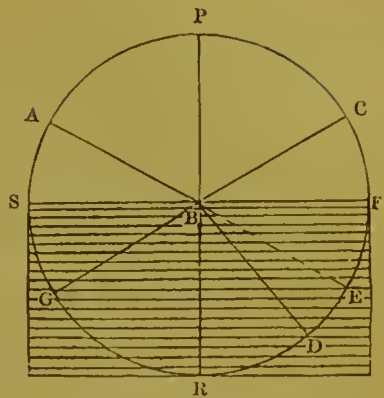

Fig. 7.

3. Reflection generally accompanies refraction; a certain portion of the light, falling upon any body, being reflected, while another portion enters the body, and is either lost within it or transmitted through it.

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[1] See Anatomical Introduction explanatory of a Horizontal Section of the Human Eyeball, by Thomas Wharton Jones, prefixed to the Author's Practical Treatise on the Diseases of the Eye.

[2] *Tunica consolidativa* of Scheiner.

[3] According to Griffin, 1° 11′ above the plane passing through the visual axis of both eyes. London Medical Gazette, xxii. 230; London 1838.

[4] *Focus*, or *burning point*, so called because the sun's rays being brought together by reflection or refraction, are sufficient to set fire to a combustible body, exposed at their point of convergence.

[5] In double refraction, such as that of Iceland spar, there is an exception, for the extraordinary ray, as it is called, lies out of the plane of incidence.

CHAPTER II.

RECTILINEAL PROGRESSION OF LIGHT, AND FORMATION OF IMAGES BY RADIATION.

§ 6. *First law of light. Its rectilineal progression.*

The first of the laws of light is, that from every luminous point, light tends to radiate in every direction, in straight lines. The flame of a candle, placed in the centre of a sphere, would, in obedience to this law, be visible at every point of that sphere.

The truth of the law is illustrated by many facts of common observation. For instance, if a beam of the sun's light is admitted into a dark room, through a small aperture, the smoke or particles of dust floating in the air, by reflecting the light, exhibit the form of the beam, which is always observed to be rectilineal.

§ 7. *Decreasing intensity of direct light.*

It follows from the rectilineal progression of light, that its intensity diminishes as the distance increases; and this in proportion to the square of the distance. The light which falls on the square A B C D, fig. 8, from the point R, at the dis-

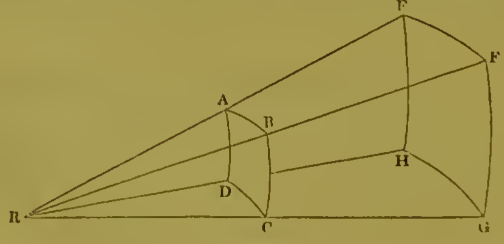


Fig. 8.

tance R A, will at twice the distance, R E, be spread over a surface E F G H, four times as large. Were light molecular, the same number of particles diffused over the first square,

would be diffused over the second. The density or intensity of the light at the first surface is to the density or intensity at the second, as the area of the second surface is to the area of the first.

§ 8. *Formation of images by radiation. Tenuity of light.*

These general facts being premised, let us take a very simple apparatus for experiment, a card, A, fig. 9, and having

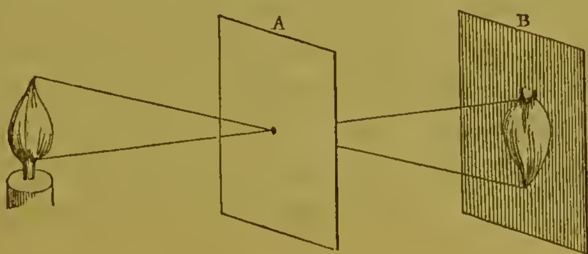


Fig. 9.

made a hole, about one-tenth of an inch in diameter, through the middle of it, let us hold it towards a lighted candle. The light, radiating in straight lines in every direction, strikes partly on the imperforated part of the card, and is thereby reflected or absorbed; but a part passes through the hole, and if we hold up a sheet of paper, B, beyond the card, we will observe an inverted image of the flame on the sheet of paper; the rays of light from the upper part of the flame, proceeding in straight lines, strike below, those from the lower part strike above, and the image is inverted. Thus it is, that, in consequence of the rectilineal progression of light, images are formed by its mere transmission through a small hole.

If we move the sheet of paper away from the card, the image enlarges; if we carry it nearer, it diminishes. If we place two lighted candles before the card, two images are formed on the sheet of paper. If we move the candle which stands nearer to us, we cause the image which is farther from us to shift, showing that the images are completely reversed. If we hold up the card towards a row of lighted candles, rays of

light flowing through the hole from all of them, form as many images on the sheet of paper as there are candles, each image being as clear and distinct as if there was only one, an experiment which illustrates the *tenuity* of light; for if it did not possess this property in a very great degree, the rays could not pass through the hole from so many different sources without confusion.

In this simple apparatus, we have the analogues of the most essential parts of the eye. The card is the analogue or representative of the *iris*, the hole of the *pupil*, and the sheet of paper of the *retina*. The rays of light from external objects, entering the eye, are partly reflected or absorbed by the iris, while the rest pass through the pupil, and arriving at the retina, form there an inverted image of those objects. Along with the formation of that image, there is an impression of an unknown nature made on the retina, and by that impression, we see.

§ 9. *Analogy of the eye to the camera obscura.*

The formation of inverted images by the transmission of radiating light through a small hole, or in other words by the exclusion of its lateral pencils, is a phenomenon with which we are familiar in another way. Every one has observed that if he is sitting in a room with the shutters all but closed, there is formed on the wall opposite to the window, or on the roof of the room, an inverted picture or image of the external scene, and of the passing objects in the street. The image is still more distinct, if the windows are completely closed, and a hole bored in one of the shutters, through which the light from without is allowed to radiate, exactly as in the experiment with the card. This is to convert the room into a *camera obscura*, fig. 10. The images are formed within the room as within the eye, and hence the eye is often called a *camera obscura*. In fact, it was this experiment which led to the discovery of the formation of the images of external objects, on the internal surface of the eye, by means of the light transmitted through the pupil.[1]

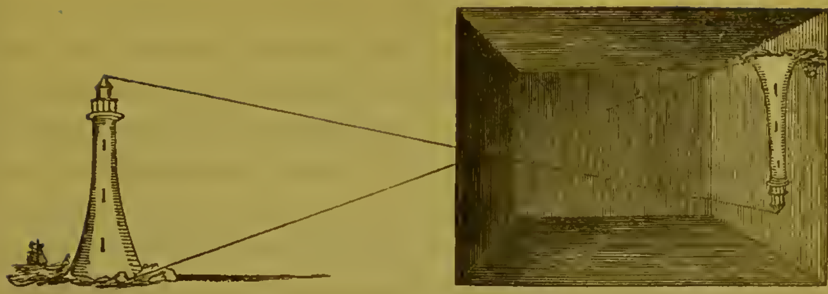


Fig. 10.

To return to our experiment with the card, we shall find that, although by enlarging the hole, more light is transmitted, the image becomes less distinct; and if the hole be much enlarged, the image totally disappears. The same thing happens with the camera obscura. Enlarge the aperture in the window-shutter, and the picture fades away. If the hole, in either case, be very small, the image is obscure, from the scantiness of the light transmitted; if enlarged, the image is lost, from the lateral pencils not being excluded. The image is most distinct, when the aperture is of a moderate size; but even then, it is impossible to form a vivid image by simple radiation.

§ 10. *Obscurity of the images formed by radiation.*

Suppose A B, fig. 11, to represent the luminous object, and A C, A D, the outermost rays of light, which, proceeding from A, can pass through the aperture C D in the card, or other opaque lamina E F, and B D, B C, the outermost rays from B. Let G H be the surface which receives the rays after

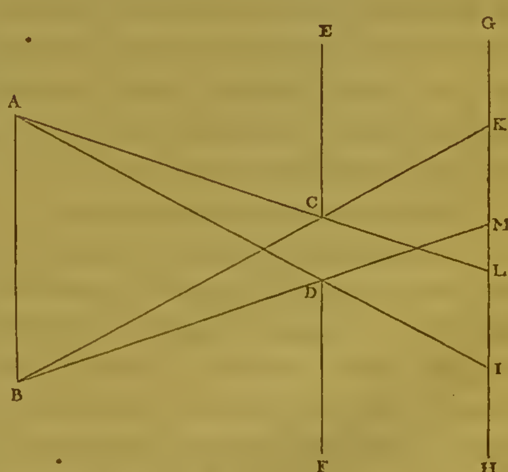


Fig. 11.

their transmission through C D. It is plain, that the rays pro-

ceeding from A, must cross those proceeding from B; and that the cone of rays from the upper extremity of the object, A, is thrown on the lower part of the surface G H, while the cone from the lower extremity, B, is thrown on the upper part of the same surface, so that, the image I K of the luminous object A B is inverted.

In the passage of the rays of light from the object A B to the surface G H, there is no concentration of the rays to focal points. On the contrary, the cone of rays A C D becomes broader and broader till it falls on the surface G H at L I, and the same holds true of B D C falling at K M, and of every cone of light which may be supposed to proceed from every point of the object A B. It is on this account that no vivid image can be formed by mere radiation. To form such an image, some contrivance must be had recourse to, which shall counteract the effect of the first law of light, and, bending the rays from their recti-lineal direction, bring each cone to a focal point.

§ 11. *Inversion of the images formed by radiation.*

The complete inversion of the image is a fact which should be particularly studied, as the same inversion takes place within the eye, where the pupil is the aperture for transmission, the iris the opaque lamina serving to exclude the lateral pencils of light, and the retina the screen for receiving the image. The simple experiment with the perforated card, the lighted candle, and the sheet of paper, sufficiently proves the fact of the inversion, which may be illustrated, however, a little more fully in the following way:—

Having arranged the apparatus so as to form a distinct inverted image, take a paper-folder, knife, or other opaque body, and bring it slowly down between the candle and the perforated card, keeping it nearer to the former than to the latter. As the folder descends between the candle and the perforation, it will be observed that that part of the image on the screen which is lowermost, becomes first eclipsed; but if the folder is brought from below, the uppermost part of the image is the first to disappear. If, again, the folder is made to de-

scend between the perforated card and the screen, closer to the latter than to the former, the uppermost part of the image is first eclipsed; if it be brought from below, the lowermost part is the first to disappear. If, again, the folder is introduced close to the perforated card, and on either side of it, the whole image is suddenly obscured. The causes of these various effects will appear at once by referring to fig. 11, in which the interior rays of light coming from the luminous object are seen to decussate before they reach the perforation; the exterior, after they have passed through it. The folder, placed near the candle, intercepts the cones A C D, B D C, before they cross; placed near the screen, it intercepts the same cones after their complete decussation; placed close to the perforation, and on either side of it, the obscuration involves rays belonging to each of the cones.

The same experiment may be performed as follows:—Close one eye, and holding the perforated card about an inch before the other, view the candle through the hole. If the paper-folder is now brought down between the candle and the perforated card, but kept nearer to the former than to the latter, the top of the flame will be eclipsed; but if the folder is brought down between the eye and the hole, and nearer to the former than to the latter, the bottom of the flame will be the first to disappear. If the edge of the folder advances in front of the eye from the right side, the left side of the hole will be darkened, and the flame will become as if eclipsed in a direction opposite to the motion of the folder. If the folder be brought in from the left, the candle will disappear from the right side. All this will be observed to happen before the folder advances so far as to be opposite to the hole in the card; the reason of which will at once appear by referring to fig. 11. If the folder is brought in on either side of the hole, and close to it, the whole flame is suddenly eclipsed.

These facts sufficiently illustrate the rectilineal progression of radiating light; and the inversion of the images formed by the exclusion of its lateral pencils.

§ 12. *Size of the images formed by radiation.*

We have already remarked that, if the sheet of paper be moved from the card, the image of the candle enlarges; if we bring it nearer, it diminishes. The *linear* magnitude of the image, formed by radiation, will bear the same proportion to that of the object, as the distance between the aperture for transmission and the screen on which the image is received bears to the distance between the same aperture and the object. The *absolute* magnitude of the image, or the surface covered by it, increases directly as the squares of the distances of the screen from the aperture of transmission; and decreases inversely as the squares of the distances of the object from the same aperture. Thus, at one inch from the aperture, the image covers a certain extent of surface; at the distance of two inches it covers *four* times that surface, at the distance of three inches, *nine* times that surface; and so on. If the object is at the distance of one inch from the aperture, the image will have a certain absolute magnitude; if the object be removed to the distance of two inches, the image will be diminished to one-fourth; if the object be removed to the distance of three inches, the image will be diminished to one-ninth; and so on.

[1] Io. Baptista Porta, Magiæ Naturalis Libri iv. fol. 119, Antverpiæ 1560.

CHAPTER III.

REFRACTION OF LIGHT.

§ 13. *Third law of light. Its refraction on passing obliquely from one medium into another of different density. Experiments showing what is meant by refraction.*

If light proceeds perpendicularly out of one medium into another, however different their densities, it continues in the same rectilineal course; but if it passes obliquely (that is, in any direction but that of a perpendicular to the plane touching the surface at the point of incidence,) out of one medium into another of different density, it deviates from its previous rectilineal course, and takes a new, but still rectilineal path within the new medium. This is the third of the laws of light.

1. Take an empty tea-cup, and place it so that the light from the sun, or from a candle falls upon it obliquely. The portion of the cup farther from the light will be illuminated, while the rest, B C E, fig. 12, will be in shadow. Let A B represent a ray of the light, passing over the edge of the cup, and falling on the bottom of it at C. If we now fill up the cup with water, a remarkable change will be observed to take place in the direction of the ray A B C. A larger portion of the interior of the cup will now be illuminated, and the shadow will be proportionably contracted, while the ray of light A B will be observed bent into the direction B D. The ray A B D has a broken appearance, in consequence of the sudden change in its direction, and on this account the change in question is styled *refraction*.

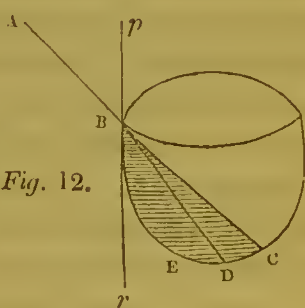


Fig. 12.

In this simple experiment, the ray of light A B has passed out of a rare medium, air, into one of considerable density, water, and it is plain that by this transition, the light has been refracted towards *p r*, a line perpendicular to the surface of the

The ray of light, S A, fig. 15, proceeding from the sixpence, must traverse the water, the saturated solution, the oil of turpentine, and the oil of anise, exactly in the same direction, to pass over the edge of the cup, and yet, on quitting these several media, it is bent by them from the perpendicular, *p r*, in different degrees *b*, *c*, *d*, *e*, in proportion to the refractive power of each. If the cup were filled with water, the eye would perceive the sixpence from *b;* if with solution of salt, from *c;* if with oil of turpentine, from *d;* if with oil of anise, from *e*.

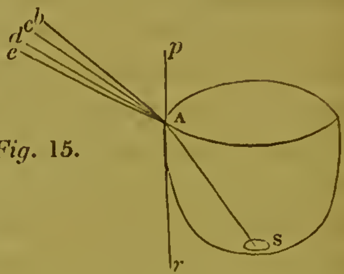


Fig. 15.

The fact that the rays of light are refracted in different degrees on quitting obliquely, as well as on entering obliquely, a dense medium, is established by various observations, and may be more fully illustrated in the following manner:—

Let A B, fig. 16, represent a ray of light, passing through air, and incident obliquely on the surface of water at B. Instead of pursuing its original course to C, it will be refracted into the direction B D, and drawn towards *p r*, a line perpendicular to the surface of the water at the point of incidence B. Let A B, fig. 17, represent a ray of light falling in like manner obliquely at B on the surface of a denser medium than water, say glass. It will be drawn still more towards the per-

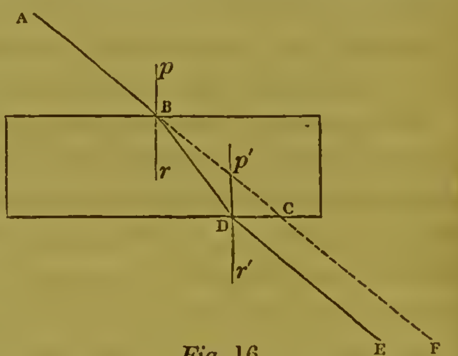


Fig. 16.

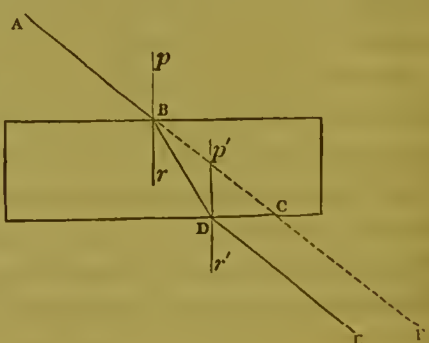
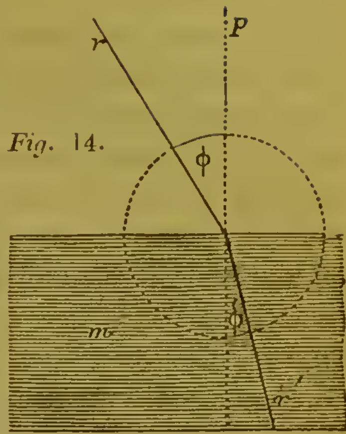


Fig. 17.

The incident ray r, fig. 14, and the refracted ray r' lie always on the opposite sides of the perpendicular, p, to the surface of the medium, m, at the point of incidence. The ray in the rare medium, r, is always farther from the perpendicular than the ray in the dense medium, r'; in other words, the angle, φ, in the rare medium, is always greater than the angle, φ', in the dense medium.

Fig. 14.



§ 14. *Power of refraction possessed by different substances in different degrees.*

Experiments, equally simple as the above, make known to us another fact, namely, that the power of refracting light is possessed by different substances in different degrees.

Returning to the first of the two experiments above related, after we have ascertained that the presence of water in the tea-cup refracts the light from its original direction into the course B D, fig. 12, if instead of simple water, we substitute a saturated solution of salt in water, we shall find that this fluid bends the light a little nearer to the perpendicular than simple water, or in other words, the solution has a greater refractive power than water. If we next try oil of turpentine, we shall find it to bend the light still more towards the perpendicular than the solution of salt, and oil of anise more than oil of turpentine.

Returning to the second experiment, after we have ascertained that the presence of water in the cup, refracts the ray S A fig. 13, into the direction A E, and enables us to see the sixpence as if at S′, if we use a saturated solution of salt, or if we use oil of turpentine, or oil of anise, we shall find that a greater bending of the ray, A E, from the perpendicular is produced by these substances than by water, and that the sixpence appears, therefore, still farther elevated than when water was employed.

The ray of light, S A, fig. 15, proceeding from the sixpence, must traverse the water, the saturated solution, the oil of turpentine, and the oil of anise, exactly in the same direction, to pass over the edge of the cup, and yet, on quitting these several media, it is bent by them from the perpendicular, *p r*, in different degrees *b*, *c*, *d*, *e*, in proportion to the refractive power of each. If the cup were filled with water, the eye would perceive the sixpence from *b;* if with solution of salt, from *c;* if with oil of turpentine, from *d;* if with oil of anise, from *e*.

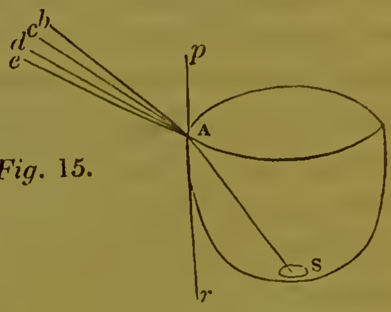


Fig. 15.

The fact that the rays of light are refracted in different degrees on quitting obliquely, as well as on entering obliquely, a dense medium, is established by various observations, and may be more fully illustrated in the following manner:—

Let A B, fig. 16, represent a ray of light, passing through air, and incident obliquely on the surface of water at B. Instead of pursuing its original course to C, it will be refracted into the direction B D, and drawn towards *p r*, a line perpendicular to the surface of the water at the point of incidence B. Let A B, fig. 17, represent a ray of light falling in like manner obliquely at B on the surface of a denser medium than water, say glass. It will be drawn still more towards the per-

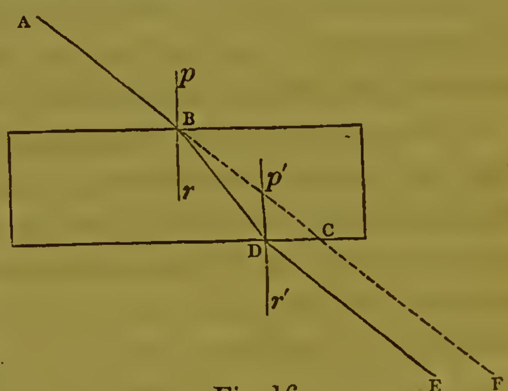


Fig. 16.

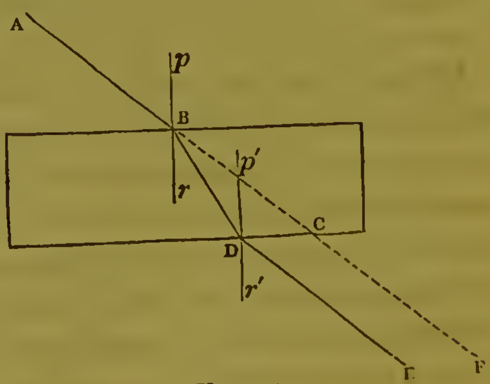


Fig. 17.

pendicular $p\ r$, being refracted into the direction B D, instead of pursuing its original course to C. If the dense medium is bounded by plane surfaces, parallel to each other, as is represented in figs. 16 and 17, on quitting the dense medium, to enter one which is less dense, say air, the ray will undergo a second and opposite refraction. The ray B D, quitting obliquely the second surface of the dense medium, is refracted from the perpendicular $p'\ r'$, and takes the direction D E, which in both cases is parallel to C F, the original course of the ray. By comparing the angle of incidence B D p' with the angle of refraction E D r', in the two cases, it will be evident that the refraction of the ray B D, on quitting the second surface is greater when the refracting medium is glass than when it is water.

§ 15. *Summary of facts regarding refraction.*

The following is a summary of the principal facts established by the preceding observations:—

Light, passing in an oblique direction, either out of a rare into a dense medium, or out of a dense into a rare medium, is refracted in different degrees according to the relative refractive powers of the two media; towards the perpendicular, if the new medium is dense, and from the perpendicular, if the new medium is rare.

§ 16. *Image of a luminous body rendered smaller and brighter by refraction through a dense medium bounded by parallel planes.*

It has already (§ 10) been explained that in the passage of the rays of light from a luminous object, through a small aperture, and through the same uniform medium, as air, the cone of rays, issuing from each luminous point, continually becomes broader and broader as it proceeds. It may here be proper to point out the influence which a dense medium, bounded by plane surfaces, would have in counteracting this, and, by refracting the transmitted rays from their rectilineal

course, render the image of the luminous object in some degree smaller and brighter.

Let us suppose, then, that C D, fig. 18, represents the

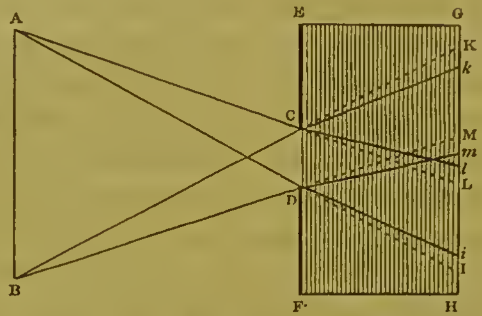


Fig. 18.

aperture of transmission, as in fig. 11, but that the space between the opaque lamina E F, and the surface G H, on which the image of A B, the luminous object, is to be received, is no longer occupied by air, but by a denser medium, as water or glass. If this were the case, the ray of light A D would no longer proceed to I, but would be refracted towards a line drawn perpendicular to the surface of the new medium, and would fall, say at *i;* the ray B C would no longer proceed to K, but would fall at *k;* the ray A C would no longer proceed to L, but would fall at *l;* and the ray B D would no longer proceed to M, but would fall at *m*. All these rays, and every other, which we may suppose to flow from the luminous object A B, and traverse the aperture C D, would thus be refracted towards the perpendicular, on meeting with the dense medium E G H F; and although the concentration of the rays of light by a dense medium, bounded by parallel planes, is not sufficient to bring the cones of rays to focal points, still it is sufficient to diminish the image on the surface G H, so that it will be comprehended between *i k*, instead of extending from I to K, as it did when no dense medium intervened.

It is plain that the image, in this case, while it is smaller, will also be brighter, for the same quantity of light which was formerly spread out over the space I K is now concentrated on *i k*.

§ 17. *By varying the obliquity of the refracting surface, rays can be refracted in any degree, and to either side.*

It being understood that the amount of the deviation of the refracted ray from its original course is always proportionate to the refractive power of the medium, it is next necessary to explain that by varying the obliquity of the surface of the refracting medium, in respect to the incident ray or rays, we are able to produce any particular deviation we wish to obtain, whether in respect to degree or direction. By varying the obliquity of the refracting surface, we are able, in the *first* place, to give to the incident ray or rays a greater or smaller deviation; and, in the *second* place, we can bend them to which side we please.

1. If we wish to produce a great degree of deviation, we give an increased obliquity to the refracting surface; if we wish a small degree of deviation, we employ a refracting surface, of which the obliquity is slight. This may be illustrated by fig. 19, in which A, B, C, D are supposed to be rays of light passing from a rare into a dense medium. The ray A meets the surface of the medium perpendicularly, that is, without any obliquity; therefore, there is no deviation. The ray B meets the refracting surface with slight obliquity; therefore, there is a small degree of deviation. The deviation of C from its original direction is greater than that of B, and that of D greater than that of C, in proportion to the increasing obliquity of the refracting surface. In the figure, all the rays are represented as coming to a focus, F, but this is not essential to the principle.

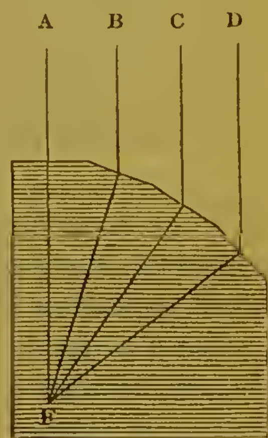


Fig. 19.

If the rays are passing from a dense into a rare medium, as

in fig. 20, the same principle is applicable. To produce a great degree of deviation, we must give an increased obliquity to the surface relatively to the ray. In A the deviation is null, because there is no obliquity. In B, C, and D, the deviation increases with the obliquity of the refracting surface.

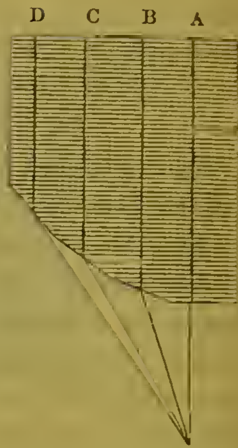


Fig. 20.

2. By varying the obliquity of the refracting surface, we are able to bend the ray to either side. As the incident and the refracted ray lie always in the same plane (§ 5), there are only two sides to which the incident ray can be bent by refraction. We may call them the *right* and *left* sides. If we wish the ray to be bent to the *right* by means of a dense medium, we must take care to place the refracting surface so that the perpendicular to it, drawn in the dense medium, shall be to the right side of the original course of the ray, and, besides, that the said perpendicular shall be farther to the right than the direction in which we wish the refracted ray to travel. Let A B, fig. 21, be a ray which we wish to bend to the right, in the direction B D, which is to the right side of B C, the original course of the ray. In order to accomplish this, we must place the refracting surface so that the perpendicular B *p* shall be to the right of B C, and that it shall be farther to the right than B D. In other words, the ray, refracted by passing into a dense medium, always lies on the same side with the perpendicular, and between it and the original course of the ray.

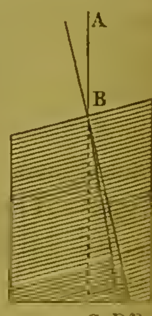


Fig. 21.

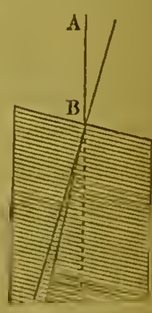


Fig. 22.

Suppose we wish the ray A B, fig. 22, to be bent to the *left* by means of a dense medium, the perpendicular B *p* must be to the left side of

the original course of the ray B C, and farther to the left than the direction B D in which we wish the refracted ray to travel.

If the ray is passing from a dense into a rare medium, the refracting surface must be so placed, that the perpendicular to it, within the rare medium, shall be on the opposite side of the original course of the ray from that to which we wish the ray to be refracted. Let A B, fig. 23, be the ray. If we wish it bent to the right, in the direction B D, we must have the refracting surface so placed, that the perpendicular B p, situated in the rare medium, shall be to the left side of the original course of the ray B C, and *vice versa.*

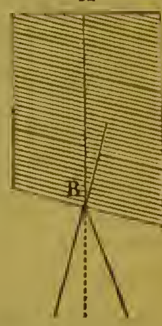


Fig. 23.

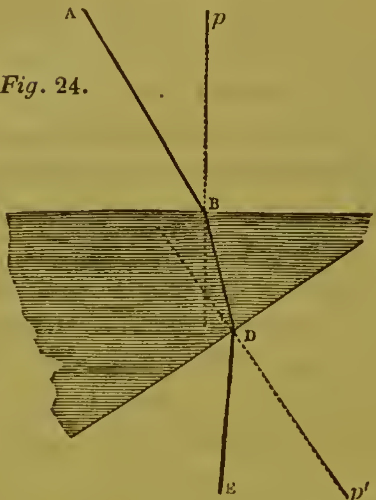
These remarks will suffice to illustrate, in a general way, the principle that within certain limits the refraction of the ray may be varied in amount and in direction, by varying the obliquity of the refracting surface relatively to the ray, whether it passes from a rare into a dense, or from a dense into a rare medium. As for the necessary calculations of the precise obliquity to be given to the refracting surface, in order to produce a given degree of refraction, these will depend on the relative refractive powers of the two media, and on a particular law of refraction afterwards to be explained.

§ 18. *Refraction by two surfaces inclined to each other.*

A slight consideration of the facts now stated will be sufficient to suggest to the reader, that if the surfaces of a dense medium be inclined to one another, the refraction which the ray will undergo at the second surface, instead of restoring it to its original course, as was the case (figs. 16 and 17,) where the surfaces were parallel, will augment its deviation. Fig. 24 represents a dense medium, with two surfaces inclined to each other. The ray A B is at the first surface refracted into the direction B D, towards the perpendicular p; but at the

second surface, it is carried into the direction D E, from the

Fig. 24.



perpendicular p'. The second refraction carries the ray still farther, then, from its original course.

§ 19. *By giving a determinate figure to the refracting surface, a pencil of rays may be bent into determinate directions.*

Admitting, then, the above principles to be established with regard to a single ray, it will follow that when a pencil of rays passes through a refracting surface, the rays may be bent into determinate directions by a determinate figure of that surface, and that variations in the figure will produce corresponding variations in the refractions.

§ 20. *A curve will bring a pencil of rays to a focus.*

It may readily be deduced from the reasonings above stated, that the surface of any medium intended to bring a pencil of rays to a focus must be a curve; and, further, that the surface of a dense medium employed for that purpose must be convex, both in the case in which we wish to produce the convergence by transmitting the rays from a rare into a dense medium, and in that where the transmission is from a dense into a rare medium.

§ 21. *Refraction of parallel rays by one convex surface.*

We now come to apply the principles, above explained, to the determination of the figure of a dense medium, which shall fit it for collecting rays to a focus.

Let the luminous object be very remote, so that the rays flowing from it may be considered as parallel to each other; for at great distances, their actual deviation from parallelism is insensible. Let A, B, C, D, E, fig. 25, represent these rays.

Fig. 25.

One only of them, C, by continuing its rectilineal course, can arrive at the point F. The surface of the dense medium should be presented at right angles to this ray, at *i*, so that it may pass through that surface without deviation. Those rays, B and D, which are situated near to the direct or central ray C, will require but a small degree of refraction to enable them to reach the focus, F, which small refraction will be effected by a slight degree of obliquity in the dense medium at the points *h* and *k*. In proportion as the rays A and E are more distant from the central ray, a greater amount of refraction, and consequently a greater obliquity of the surfaces at *g* and *l*, will be required, to bring them to the same focus. On the presumption that the rays passed through a medium of uniform density, they would converge to a focus, then, at F.

The convergence of the rays, after they have passed the surface *g h i k l*, may be farther increased, by interposing new surfaces of other media. If a new medium of greater density than the first be employed, the inclination of its surface will require to be similar to that already described, that is to say,

it must present a convex surface to the incident rays; but if it be rarer, the inclination will require to be in an opposite direction, and the surface concave.

§ 22. *Refraction of parallel rays by two convex surfaces.*

Let fig. 26 represent the rays A, B, C, D, E, entering the

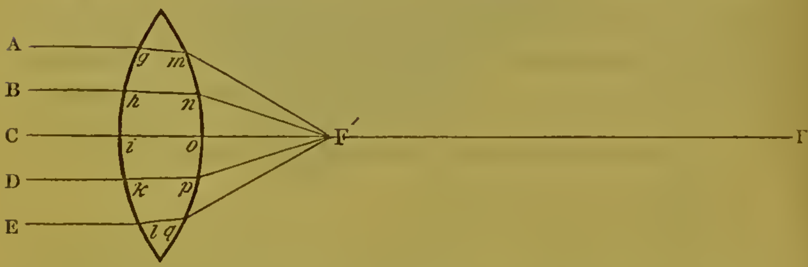


Fig. 26.

dense medium as before, but instead of the same medium being continued, let it be supposed to terminate at the curved surface *m n o p q*, so that it now forms a double-convex lens. The central ray C proceeds at right angles through both surfaces, and reaches F′ or F, without deviation. The rays B, D, A, E are refracted towards the perpendiculars on passing into the dense medium at the points *h*, *k*, *g*, *l*, but on quitting it, they are refracted from the perpendiculars to the surface of the rare medium at the points *n*, *p*, *m*, *q*. This new refraction increases the convergence of the rays, and brings them to a focus F′, nearer to the dense medium than the former focus F.

The result of the continual change of direction in the refracting medium, is a regular curvilineal surface, approaching to the spherical. By giving to refractive substances such surfaces, they are adapted to produce with more or less exactness the convergence of parallel rays to a focus, and by making the dense medium convex on both sides, both conspire to produce the desired effect.

The distance of the focus behind the medium depends on the refracting power of the substance employed, and on the degree of convexity of its surfaces. The greater the convexity of the two surfaces, and the greater the refractive power, the nearer the focus.

§ 23. *Formation of images by a double convex lens.*

Having thus obtained, then, the instrument called a *double-convex lens,* we might venture to enlarge the aperture through which the light was admitted into the dark room or *camera obscura* (§ 9), and fit such a lens into the aperture. The light flowing from external objects will be refracted by the lens, and the image, which otherwise was diffused, dim, and indistinct, will become concentrated, vivid, and clear.

Returning to our former train of reasoning (§ 10 and 16), let us suppose the aperture C D, in the opaque lamina E F, fig. 27, to be enlarged, and to be occupied by a double-convex lens, of which the focal length is equal to the distance

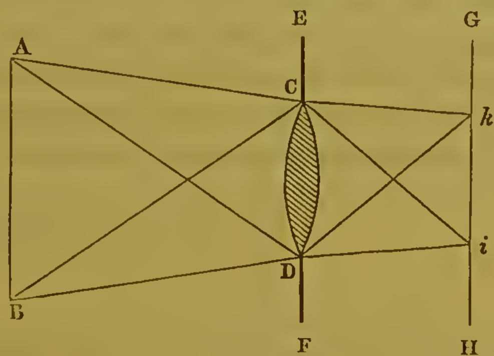


Fig. 27.

between the aperture C D, and the screen G H. The cone of light issuing from A, being refracted by the lens, will be concentrated to a point at *i*, the cone of light from B will be brought to a focus at *k*, and those from every intermediate point of the object A B will form corresponding focal points, so that an inverted image of the object will appear on the screen G H. The whole of the light radiating from A B, and falling on the surface of the lens, will be concentrated on the space *i k*, and the image will of course be much more vivid than when formed by the mere exclusion of the lateral pencils of light as in fig. 11, or by the refraction of a dense medium bounded by parallel planes, as in fig. 18.

CHAPTER IV.

MEASUREMENT OF REFRACTION.

§ 24. *Refraction not to be measured by the angles of incidence and refraction.*

It is important that we should be able to measure refractions, and to compare by measurement the refractive power of one substance with that of another.

It might at first sight appear that refractions ought to be measured simply by comparing the angles of refraction, or those of deviation, with those of incidenee; but this is not the case. Before stating the true method of measuring refractions, it is necessary to explain what is meant by the *sines* of angles.

§ 25. *Sines of angles explained. Ratio of the sines different from the ratio of the angles.*

The sine is a perpendieular from one end of the are, which measures any angle, to the other side of the angle, or to that side produced.

That the sines of angles increase less rapidly than the angles themselves, or the arcs which measure the angles, may be shown thus:—Let A B, fig. 28, be the arc which measures any angle A O B, and A C the double of it. Draw A M the sine of the angle A O B or arc A B, A N the sine of the angle A O C or arc A C, and A C the chord of the arc A C. Then, the chord A C is [1] double of A M, the sine of the are A B. But in the triangle A N C, the side A C is greater than A N, because A N C is a right angle; therefore, the sine A N is less than double

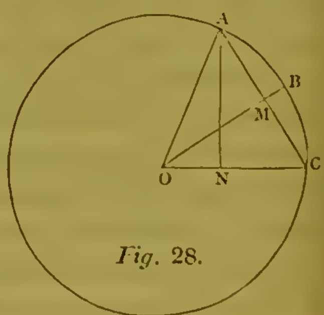


Fig. 28.

the sine of half the arc A C. Consequently, the arcs of a circle increase in a more rapid ratio than the sines of those arcs.

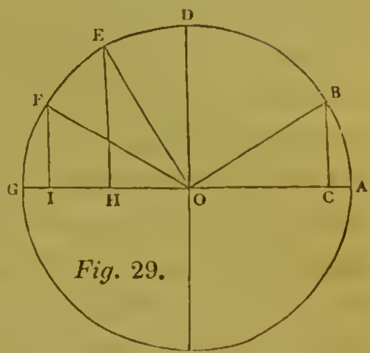


Fig. 29.

That the sines of angles have not the same ratio to one another as the angles themselves, or the arcs which measure the angles, will further appear obvious from an examination of fig. 29.

Agreeably to the above definition of a sine,

B C is the sine of the angle B O A, or of the arc B A, of 30°
D O ... ... D O A, ... D A, ... 90°
E H ... ... E O A, ... E A, ... 120°
and F I ... ... F O A, ... F A, ... 150°

Now, if the sines had the same ratio as the angles, the sine D O of 90° would be *three* times the length of the sine B C of 30°; the sine E H of 120° would be *four* times the length of B C; and the sine F I of 150° *five* times the length of B C; all which is evidently not the case.

§ 26. *Experimental measurement of refraction.*

These things being understood, suppose a circle A B C D, fig. 30, to be described upon a plate of metal, and let A C, B D be two diameters perpendicular to each other. Immerse the plate in a vertical position in a vessel of water, so that the surface of the water shall coincide with the diameter B D. Were a ray of light, A E, to fall in a perpendicular direction on the surface of the water at E, it would proceed in the same straight line to the point C, as has already (§ 13) been stated. A ray may fall upon E with any degree of obliquity between

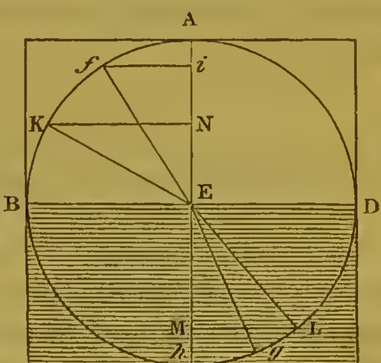


Fig. 30.

A E and B E, or, in other words, the angle of incidence may vary from 0 up to 90°. Were a ray to fall in the oblique direction *f* E, it would be refracted by the water at E, in the direction E *g*, and strike the circle at *g*. The angle *f* E A, which the incident ray forms with the perpendicular, A C, is the angle of incidence; and the angle *g* E C, which the refracted ray E *g* forms with the same perpendicular, is the angle of refraction. These angles were formerly believed [2] to be in a constant ratio to one another, so that by measuring them, it was supposed that the refractive power of water or any other medium, was determined. When the angles, indeed, are small, or, in other words, when the incident ray divaricates little from the perpendicular, the error readily escapes detection; but whenever the angles of incidence and of refraction become great, it might have been observed that their ratio no longer continues the same, but varies with every different inclination of the incident ray, and cannot therefore afford a true measurement of refractive power. For example, the angle *f* E A is one of 20°, and the angle of refraction *g* E C is equal to 14° 30′; but suppose a ray of light K E to fall at an angle of 60°, the angle of refraction out of air into water, L E C, would be found to measure only 40° 24′; but the ratio of 20° to 14° 30′ is not the same as that of 60° to 40° 24′. Some other method of measuring refractions, therefore, required to be discovered.

§ 27. *Measurement by means of the sines of the angles of incidence and refraction. Law of refraction.*

Snell[3] and Des Cartes[4] were the first to point out, that, although the ratio of the *angles* of incidence and of refraction is variable, the *sines* of these angles are in a constant ratio, however varied the incidence of the light, provided the two media through which it passes continue the same. This discovery afforded the means desired, furnished the *law of refraction*, and became in fact the foundation of dioptrics.

Draw *g h*, fig. 30, the sine of the angle *g* E C, and *f i*, the sine of the angle A E *f*, the refraction being, as we have sup-

posed, out of air into water. Measure the length of these sines on a scale of equal parts, and it will be found that *f i* is greater than *g h* in the ratio of about 4 to 3, or more correctly of 1.336 to 1. Were the ray to fall in any other oblique direction, as K E, and to be refracted in the direction E L, and the sines K N and L M to be drawn, and measured, as before, it would be found that K N is greater than L M, still in the same ratio of 4 to 3 or of 1.336 to 1. If instead of measuring the sines of the angles of incidence and refraction, out of air into water, in the manner above mentioned, we were to measure the angles, and then take the length of their sines from a table of natural sines, they would be found, whatever might be the extent of the angles, to have to one another the same invariable ratio of 1.336 to 1, which is nearly as $1\frac{1}{3}$ to 1, or 4 to 3.

When the ray *f* E passes from air into water, the continuation of that ray E *g* is refracted towards the perpendicular, and the sine of the angle of refraction being assumed equal to 1, the sine of the angle of incidence will be equal to 1.336; but were the ray *g* E to pass from water into air, E *f* would be refracted from the perpendicular E A, and the sine of the angle of refraction *f i* being still assumed equal to 1, the sine of the angle of incidence *g h* becomes equal to .75, the ratio of the sines being now the inverse of what it was in the former case.[5]

Were a similar experiment to the above tried with other transparent bodies, we should find, that, while the refractive power of any one substance is always different from that of every other, the same law of refraction, that is to say, a constant ratio of the sines of incidence and refraction, holds with respect to all substances. The refractive power, however, of bodies may be ascertained more conveniently by other experimental methods, and especially by giving to the medium to be tried the form of a triangular prism, and observing the deviation which a ray of light undergoes by passing through two inclined surfaces. (§ 38.)

§ 28. *Index of refraction, absolute, and relative.*

When we wish to express the refractive power of any medium, we must compare it with that of some other medium. If we compare it to vacuum, we speak of its *absolute* refractive power; if we compare it to any material substance, we speak of its *relative* refractive power.

If a ray of light passes obliquely from vacuum into the medium, whose refractive power we wish to denote; by dividing the sine of the angle of incidence by the sine of the angle of refraction, we obtain a numerical value of the ratio of these sines, which is called the *absolute index of refraction* of the medium in question. In optical discussions, when a single medium only is specified, the other is understood to be vacuum, and when we speak of the *index of refraction* of any substance, the *absolute index* is generally meant. By always representing the sine of the angle of refraction, out of vacuum into any other medium, by 1, (the number chosen to represent the refractive power of vacuum), the sines of the angles of incidence in all cases refer to the same unit of comparison. They are therefore at once comparable with each other, and by expressing the degree of the refractive power, they become the *absolute indices* of refraction. Thus, were a ray of light to pass obliquely from vacuum into atmospheric air, the ratio of the sines of incidence and refraction would be found to be as 1.000294 to 1; if from vacuum into water, as 1.336 to 1; if from vacuum into glass, as 1.531 to 1. These numbers, then, 1.000294, 1.336, and 1.531, are the absolute indices of refraction of air, water, and glass.[6]

If a ray of light passes obliquely out of one substance into another, the index of refraction is *relative*, and is obtained by dividing the absolute index of refraction of the second medium by that of the first. Thus, to find the *relative index* of a ray passing from water into glass,

$$\frac{1.531}{1.336} = 1.1459.$$

§ 29. *Refractive powers of different substances.*

Tables have been published by different observers, of the refractive powers of a great variety of substances. In such tables, (of which the following may serve as a specimen,) refraction is always supposed to take place out of vacuum into the particular medium mentioned, and the values given, unless the contrary is expressed, belong to the rays of mean refrangibility :—

Vacuum	1.
Atmospheric air	1.000294
Tabasheer	1.1111 to 1.182
Ice	1.307
Water	1.336
Sea water	1.343
White of egg	1.351
Ether	1.358
Alcohol	1.372
Sulphuric acid	1.435
Olive oil	1.467
Oil of turpentine	1.475
Camphor	1.487
Bees' wax	1.512
Plate glass	1.526 to 542
Crown glass	1.531 to 1.563
Amber	1.547
Quartz	1.548
Flint glass	1.576 to 1.642
Oil of anise seed	1.601
Oil of cassia	1.641
Ruby	1.779
Zircon	1.95
Sulphur	2.115
Phosphorus	2.224
Diamond	2.439
Chromate of lead	2.926

§ 30. *Refractive powers proportionate to the density and inflammability of bodies.*

On comparing the refractive powers of bodies with their specific gravities, it is found, that, in general, the refractive power increases with the density of the body. This, however, is not universal. Alcohol, ether, and olive oil, for instance, which are lighter than water, have a higher refractive power. The refractive power of oily substances, or inflammable bodies, is greater than that of incombustible substances of equal density. Newton observed[7] this fact with respect to amber, oil of turpentine, linseed oil, olive oil, and camphor, which he says "are fat sulphureous unctuous bodies;" and as he found the same high refractive power in the diamond, he inferred that it "probably is an unctuous substance coagulated." Since his time, its inflammable nature has been discovered. Observing, also, that the refractive power of water is great for its density, he seems to hint that an inflammable substance may enter into its composition, a conjecture which has been confirmed by one of the most unexpected results of chemical analysis.

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[1] Euclid, Book iii. prop. 3.

[2] Vitellonis Opticæ Libri x. 412; Basileæ 1572. Kircheri Ars Magna Lucis et Umbræ, 682; Romæ 1646.

[3] Hugenii Opuscula Postuma, 2. Lugduni Batavorum 1703.

[4] Des Cartes, Discours de la Méthode pour bien conduire sa Raison, 114; Paris 1668.

[5] If the ratio of the sine of the angle of refraction to that of the angle of incidence, out of air into glass, is as 2 to 3, then, reciprocally, the sine of refraction is to that of incidence, in the passage from glass into air, as 3 to 2. If from glass into water, the ratio is as 8 to 9, reciprocally, from water into glass, it will be as 9 to 8.

[6] If i and r denote the angles which the portions of the ray in the rare and in the dense medium, respectively, make with the perpendicular, the law of refraction will be expressed by the equation

$$\frac{\text{sine } i}{\text{sine } r} = \mu, \text{ or sine } i = \mu . \text{ sine } r$$

μ being a constant quantity, dependent on the nature and density of the two media.

This constant is the *index of refraction*, and since, when the refraction is from a rare into a dense medium, i is greater than r, it is evident that μ is always in those circumstances greater than unity.

When the refraction is from a dense into a rare medium, although the former angles of incidence and refraction exchange names, their sines still retain their relative value. Thus μ being the index of refraction when the light passes from one medium into another, $\frac{1}{\mu}$ is the index of refraction when it returns from the second into the first. In the case of light passing from vacuum into water, $\mu = \frac{1.336}{1}$; when it passes from water into vacuum, $\frac{1}{\mu} = \frac{1}{1.336} = \frac{.75}{1}$.

The greatest absolute value of μ is 2.926, which is the index of refraction for a ray proceeding from vacuum into chromate of lead; and between this extreme value of μ and unity, it is found of every intermediate magnitude.

[7] Opticks, 249; London 1730.

CHAPTER V.

APPLICATION OF THE LAW OF REFRACTION.

§ 31. *Determination of the course of refracted rays.*

By means of the law of the sines, it is easy to determine the course of a ray, or pencil of rays, through any medium, whatever be its form, provided we know its refractive power, and the inclination of the incident rays. With these data, the course of refraction can be obtained, either by calculation or by geometrical construction.

§ 32. *Geometrical determination of the course of rays refracted at a plane surface.*

If a ray falls on a plane surface, the following rules will enable us to trace its path, by a geometrical construction :—

1. Draw a perpendicular to the refracting surface through the point of incidence, and it will form with the incident ray the angle of incidence.

2. With the point of incidence as a centre, and any convenient radius, describe a circle.

3. From the point in the incident ray cut by the circumference of the circle, draw a line at right angles to the former perpendicular, to represent the sine of the angle of incidence, and measure this sine on a scale of equal parts.

4. Find a fourth proportional to the index of refraction of the medium, unity, and the numerical value of the sine of the angle of incidence, as determined by the scale of equal parts.

5. Measure this fourth proportional on the same scale, and mark the length of it outwards from the point of incidence, on that part of the surface of the medium which is on the opposite side of the perpendicular from the angle of incidence.

6. From the extremity of the fourth proportional, thus marked, draw through the medium a parallel to the first perpendicular, and the point where this parallel will cut the circumference of the circle is that through which the refracted ray will pass.

7. A line from that point at right angles to the first perpendicular will be the sine of the angle of refraction.

Let it be required, then, according to this method, to find the direction of a ray F C, fig. 31, after it is refracted at the surface S S′ of water. Through the point of incidence C, draw P R, perpendicular to S S′; and with C as a centre, and C F as a radius, describe a circle. From F, the point where the incident ray is intersected by the circumference of the circle, draw F I perpendicular to P C. Measure the sine F I on a scale of equal parts, and find a fourth proportional to the index of refraction 1.336, 1, and

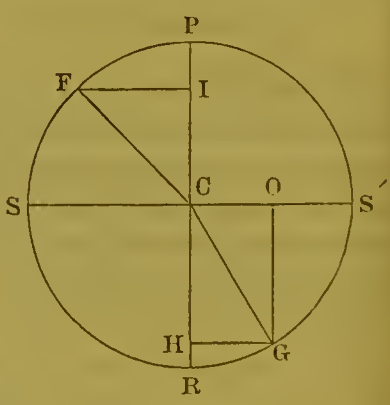

Fig. 31.

the length of the sine F I. Take the length of this fourth proportional from the same scale, and make C O equal to it; then through O draw O G parallel to P R, and meeting the circumference in G; C G will be the course into which the incident ray F C will be refracted by the water.[1] The line G H, perpendicular to C R, is the sine of the angle of refraction.

§ 33. *Geometrical determination of the course of rays refracted at a curved surface.*

If the ray falls on a spherical surface, whether convex or concave, its path may be traced by means of the following rules:—

1. Take two points, equidistant from the point of incidence, on the refracting surface, or that surface continued, and join these points by a straight line, which will be a chord.

2. Through the point of incidence draw a straight line, cutting the chord at right angles, and it will form with the incident ray the angle of incidence.

The remaining steps of the construction are precisely the same as those numbered 2, 3, 4, 5, 6, 7, in the case of rays refracted at a plane surface, except that the length of the fourth proportional referred to in rules 4 and 5, must be laid on the chord, from the point where it is intersected by the perpendicular, and on the opposite side from the angle of incidence.

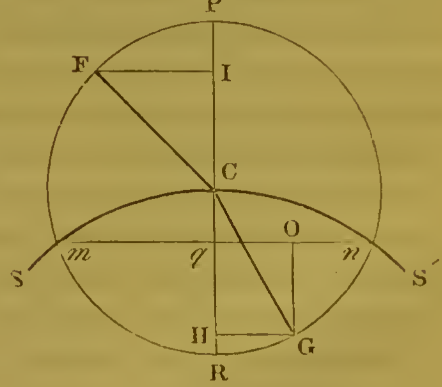

Fig. 32.

Let it be required, then, to find the direction of a ray F C, fig. 32, after it is refracted at the surface of a sphere of glass, whose index of refraction is 1.5, and of which S S′ is a segment. Let *m* and *n* be two points on the spherical surface, equidistant from C the point of incidence. Join *m* and *n* by a chord, and through C draw P R, cutting the chord at right angles in

q. C q, continued, passes through the centre[1] of curvature of the medium S S′. With C as a centre, and C F as a radius, describe a circle. From F, where the incident ray is intersected by the circumference of the circle, draw F I, perpendicular to P R. Measure the sine F I on a scale of equal parts, and find a fourth proportional to the index of refraction 1.5, 1, and the length of the sine F I. Take the length of this fourth proportional from the same scale, and make q O equal to it; then through O draw O G parallel to P R, and meeting the circumference in G. C G will be the direction in which the incident ray F C will pass through the glass. The line G H, perpendicular to P R, is the sine of the angle of refraction.

§ 34. *Sources of embarrassment in tracing refracted rays by geometrical construction. Change from refraction to reflection at the interior surface of a dense medium. Critical angle.*

The student should make himself familiar with the method of tracing by geometrical construction, the path not merely of single rays, but of pencils of rays, of different degrees of divergency and convergency, from rare into dense media, and from dense into rare, and at plane, convex, and concave surfaces. In the cases which he will propose to himself, he is likely to meet with some sources of embarrassment, against which it is proper to warn him. One of these is the *aberration of sphericity*, a subject which he will find explained in a subsequent chapter. There is another circumstance which might perplex him, namely, that light, falling on the interior surface of dense media, is not always transmitted, but sometimes totally reflected.

The minimum angle of incidence is zero; in which case, the ray, coinciding with the perpendicular, passes straight on, suffering no refraction. The maximum angle of incidence or of refraction is 90°, or a right angle, and the sine of this angle is the greatest of any, being equal to radius. At any angle of incidence, from 0 up to 90°, a ray of light can pass from a rare into a dense medium, and be refracted. But a ray traversing a dense medium, and incident on the surface of a rare medium, is not intromitted and refracted, unless it falls within a

more limited range. Were the angle of incidence in the dense medium to surpass a certain extent, the angle of refraction, in order that the ray might be refracted, would require to exceed 90°, but as this is impossible, the ray in such circumstances does not pass into the rare medium, but is totally reflected. The angle of incidence in the dense medium, beyond which the ray is no longer refracted, but reflected, is called the *limiting* or *critical angle*. It is different in extent in different media.

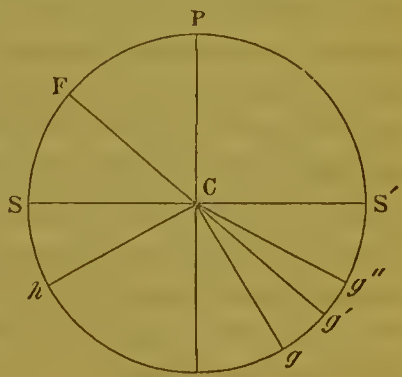

Fig. 33.

Let s s′, fig. 33, represent the separating surface of vacuum and water. A ray, incident at any angle, from nothing to a right angle, will pass into the water and be refracted towards the perpendicular C R. F C, for example, will be refracted in the direction C *g*; also a ray, *g* C, will pass out of the water into vacuum, and be refracted from the perpendicular P C, in the direction C F. But suppose a ray *g′* C to have a somewhat larger angle of incidence, so that the angle of refraction is just a right angle, and its sine therefore equal to radius, the emergent ray will then coincide with the surface C S. The angle *g′* C R, in this case, is the *limiting* or *critical angle*, for if the angle of incidence be increased, as it would were *g″* C the course of the incident ray, the ray would not emerge at all, but, instead of being refracted, would be reflected, within the water, into the direction C *h*, making the angle of reflection R C *h* equal to the angle of incidence R C *g″*. Experiment has shown that the critical angle for vacuum and water is equal to 48° 27′ 40″; for vacuum and crown glass, 40° 39′; for vacuum and flint glass, 38° 41′; for vacuum and diamond, 23° 42′; for vacuum and chromate of lead, 19° 28′ 20″.[2]

The sudden change from refraction to reflection, in such cases, is one of the most curious and interesting phenomena in optics. Being total, the reflection far surpasses in brilliancy what can be obtained by any other means. It may be

familiarly shown by filling a common drinking glass with water, and holding it above the level of the eye. If we then look obliquely upwards through the water, we shall see its whole upper surface shining, by reflection, like polished silver; and any object as a spoon, immersed in it will have its immersed part reflected from that surface as from a mirror.

The range within which total reflection takes place, does not depend alone on the density of the reflecting medium, but also on the rarity of the medium adjacent to it. The extent of that range varies with the difference of the densities, or, in other words, with the relative index of refraction, (§ 28,) of the two media. When, therefore, the refractive power of one medium is known, that of any rarer medium may be learned, by examining at what angle a ray of light will be reflected from it. This is the principle of Wollaston's method of measuring refractive powers.[3] The property of internal reflection is also employed to great advantage in the instrument called a *camera lucida*.

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[1] Euclid, Book iii. Cor. Prop. 1.

[2] The natural sine of the critical angle, for a ray passing from a vacuum into any other medium, is found by dividing 1 by the absolute index of refraction; but if the ray passes from any material medium into a denser one, the natural sine of the critical angle is equal to unity divided by the relative index of refraction of the two media. These rules are derived from supposing the natural sine of 90° equal to unity. For in this case

$$\frac{1}{\text{sine } r} = \mu, \text{ or sine } r = \frac{1}{\mu},$$

in which formula μ represents the *absolute* index of refraction, when the ray passes from vacuum into any material medium; and the *relative* index, when the ray passes from a material medium into one of greater density. Thus, the critical angle of water in relation to vacuum is 48° 27′ 40″, for in this case $\frac{1}{\mu} = \frac{1}{1.336} = .748503$, which in the table of natural sines corresponds to the angle 48° 27′ 40″.

[3] For an account of Wollaston's instrument for determining the refractive density of solid and fluid substances, by ascertaining the angle at which light begins to be totally reflected from the common surface of a glass prism and of the substance to be examined, see Philosophical Transactions for 1802, p. 365; or Young's Lectures on Natural Philosophy, i. 421; London 1807.

CHAPTER VI.

FORMS OF REFRACTIVE MEDIA, AND THEIR EFFECTS ON THE DIRECTION OF THE RAYS OF LIGHT.

§ 35. *Forms of refractive instruments.*

We must now direct our attention somewhat more particularly to the forms given to refracting media, to suit them for the purposes of optical experiments, or the formation of optical instruments. As certain of those forms, or of forms analogous to them, exist in the humours of the eye, and in one of its coats, a knowledge of their general effects is important in relation to the function of vision, as well as to the aid which vision derives from art.

Refractive instruments, as prisms and lenses, are always supposed to be denser than the ambient medium, unless the contrary is specified.

The substance most frequently used for refracting the rays of light, in optical experiments and instruments, is glass, which for these purposes is shaped into the forms, sections of which are shown in fig. 34, the opposite sides being ground into regular and polished surfaces.

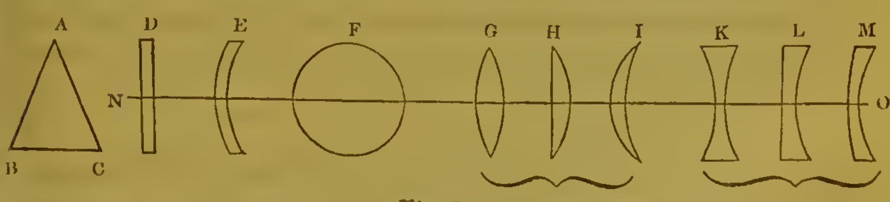

Fig. 34.

1. Any portion of a transparent substance comprised between two plane surfaces, inclined towards one another, constitutes a *prism;* although more commonly the term is applied to a solid having three plane surfaces, any two of which, A B, A C, through which light is allowed to pass, are called its refracting

surfaces, and may be inclined to one another at any angle. The face, B C, equally inclined to the refracting surfaces, is called the *base*, and the opposite angle, A, the *refracting angle*, or *vertex* of the prism.

2. A *plane glass*, D, has two plane surfaces parallel to one another.

3. A *bent glass*, E, has two curved surfaces concentric to one another, as a watch-glass.

4. A *sphere* or *spherical glass*, F, has every point in its surface equally distant from a common centre.

5. A *double-convex lens*, G, is bounded by two convex spherical surfaces, whose centres are on opposite sides of the lens. It is *equally convex*, when the radii of both surfaces are equal; and *unequally convex*, when the radii or distances are unequal.

6. A *plano-convex lens*, H, is bounded by a plane surface on the one side, and a convex on the other.

7. A *meniscus* (that is, a little moon, or crescent, from μήνη, moon), I, is bounded by a concave and a convex surface, and these two surfaces meet, if continued.

8. A *double-concave lens*, K, is bounded by two concave spherical surfaces, whose centres are on opposite sides of the lens.

9. A *plano-concave lens*, L, is bounded by a plane surface on the one side, and a concave on the other.

10. A *concavo-convex lens*, M, is bounded by a concave and a convex surface, the radius of the concave surface being shorter than that of the convex.

Supposing the sections from D to M to revolve round their axis N O, they would generate the different solids they represent.

§ 36. *Refraction of parallel rays by a homogeneous medium bounded by parallel planes.*

Parallel rays retain their parallelism, after passing obliquely through a homogeneous medium bounded by parallel planes; so that the only effect is a slight lateral displacement of the whole pencil, which produces no alteration in the apparent

place of a distant luminous point, seen through the medium. Window glass, for instance, does not alter the apparent position of objects seen through it, except where its two surfaces happen not to be parallel.

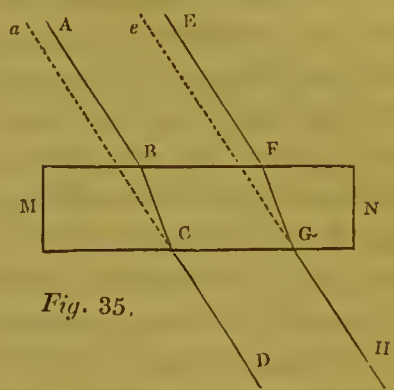

Fig. 35.

Let M N, fig. 35, be a plane glass, and A B a ray of light, refracted at B on entering the glass, into the direction B C, and at C on quitting the glass, into the direction C D. If we determine the course of the refracted ray by construction (§ 32), we shall find that C D is parallel to A B; for however much A B is bent at the first surface, it is bent as much in the opposite direction at the second. To an eye at D it will appear as if it came in a direction *a* C, which will be found by continuing D C backwards. If we conceive B C to be a refracted ray, falling at equal angles upon the two surfaces of the glass, and moving either towards A or towards D, it will suffer equal refractions at B and C, and consequently the angles which the refracted rays, B A, C D, form with the two refracting surfaces will be equal, and the rays parallel.

If we suppose another ray E F, parallel to A B, to fall upon the point F, it will suffer the same refraction at F and G, and will emerge in the direction G H, parallel to C D, as if it came from a point *e*.

§ 37. *Refraction of diverging and converging rays by a homogeneous medium bounded by parallel planes.*

Let A B, A B′, fig. 36, be rays diverging from A, and falling upon a dense homogeneous medium, such as a plane glass M N. They will be refracted into the directions B C, B′ C′, by the first surface, and C D, C′ D′, by the second. By continuing C B, C′ B′ backwards, they will be found to meet at *a*, a virtual focus (§ 4) farther from the glass than A.

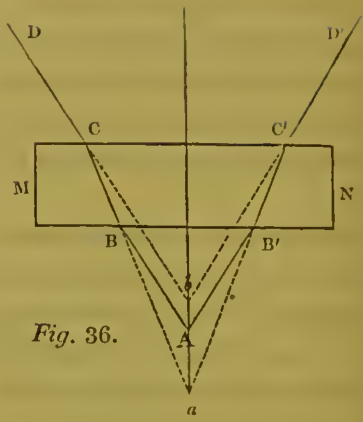

Fig. 36.

When the rays B C, B′ C′ suffer a second refraction, D C, D′ C′ continued backwards will meet at *b*, a virtual focus nearer the glass than A. The rays A B, A B′, being rendered more divergent by the last refraction, the object at A will now seem to be brought nearer to the glass, by a distance equal to one-third of its thickness. The apparent distance of the radiant point of diverging rays is diminished, then, by such a medium as a plane glass. To an eye in the air, the depth of a pond, for this reason, appears less than it really is.

If D C, D′ C′ be rays converging to *b*, and incident at C, C′, they will be made to converge to A, by the refraction of the two surfaces. A plane glass causes the focus of converging rays to recede from it.

§ 38. *Refraction by prisms. Experimental measurement of refraction resumed.*

From what has already been said (§ 7, 8.) regarding the effects of varying the obliquity of refracting surfaces and inclining them to one another, it will readily be understood, that when a ray of light passes through two planes, meeting in an angle, and bounding a dense medium, as in the case of a triangular prism, the total deviation of the ray is always from the vertex.

If the ray falls, however, on the second surface at an angle of incidence greater than the critical angle, the ray suffers total reflection (§ 34) within the prism.

If the refracting angle, A, fig. 34, be double the critical angle, none of the rays which enter at the first surface, A B, can emerge at the second, A C, but will all be reflected towards the base, B C.

When the refracting angle is equal to the critical angle, any ray, incident between the perpendicular and the base, can emerge at the second surface; all that are incident between the perpendicular and the vertex will be reflected.

When the refracting angle is less than the critical angle, all the rays which fall between the perpendicular and the base emerge at the second surface; as do a few of the rays which fall on that side of the perpendicular which is towards the vertex. When they divaricate much from the perpendicular, they are reflected. In proportion as the refracting angle diminishes, the number of rays which can emerge increases.

The direction of the emergent ray, in every case, depends on the relative index of refraction of the prism and ambient medium, on the extent of the refracting angle of the prism, and on the angle of incidence at the first surface.

Let A B C, fig. 37, be a prism of plate glass, whose index

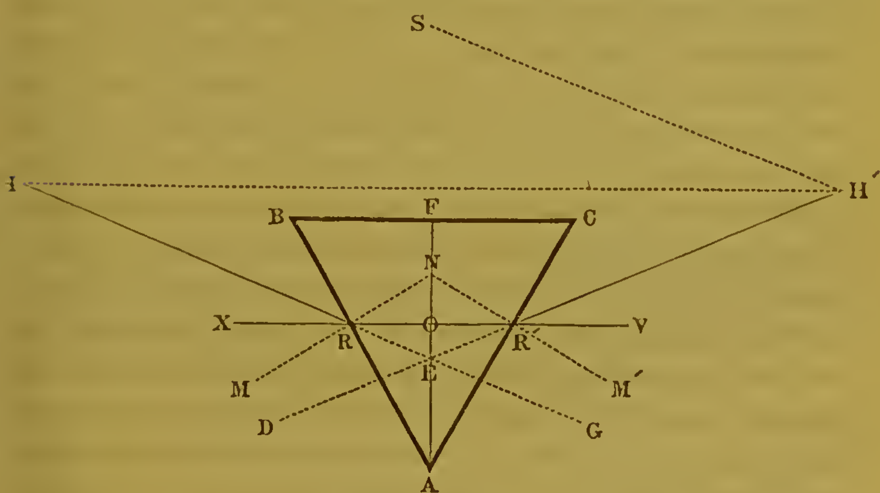

Fig. 37.

of refraction is 1.5, and let H R be a ray falling obliquely upon its surface A B, at the point R. Tracing this ray by construction, R R′ will be found to be in the direction in which it will be refracted by the prism till it reaches the second surface at R′, and R′ H′ the direction in which it will be refracted on quitting the prism at R′.

If H R R′ H′ be the ray refracted at the two surfaces of the prism, M N, N M′ perpendiculars to the surfaces at the points

of incidence and emergence, H G, H′ D the incident and emergent rays produced, and R R′ V the direction of the refracted ray within the prism produced, then

H R M is the	first angle of	incidence,
N R R′	... ...	refraction,
E R R′	... ...	deviation,
R R′ N is the	second angle of	incidence,
M′ R′ H′	... ...	refraction,
V R′ H′	... ...	deviation.

V R′ H′ = E R′ R ; and E R R′ + E R R = H′ E G = E R′ R + V R′ H′.[1]

If we suppose the original ray H R to proceed from a candle, and if we place our eye at H′, behind the prism, so as to receive the refracted ray R′ H′, it will appear as if it came in the direction D R′ H′, and a coloured image of the candle will be seen in that direction. The angle H′ E G, which the original direction of the ray H G makes with its last direction E H′, is called the *total deviation*, and is composed of the two partial deviations E R′ R and V R′ H′.

In fig. 37, the ray H R is drawn so as to make the angles which the refracted ray, R R′, forms with the faces A B, A C of the prism equal, or R R′ parallel to B C ; and in this case it follows that the first angle of incidence H R M is equal to the second angle of refraction M′ R′ H′. If the first angle of incidence, H R M, is made either greater or less, it will be found that the angle of total deviation, H′ E G, becomes greater.

If we place the eye behind the prism at H′, and look at the refracted image of the object, H, we shall observe, on rotating the prism in the plane A B C, a change in the position of the image, arising from a change in the deviation. But there is one position of the prism in which the image will appear stationary, and then if the rotation of the prism is continued, the image will move back towards its former place. At the instant when the image appears stationary, the deviation is a minimum, that is, less than in any other position of the prism. When this minimum is obtained, the angles H R R′ and R R′ H′ are equal, and R R′ is parallel to B C and perpendicular to F A, a line bisecting the refracting angle of the prism. In the triangles N R O, R A N, the angle R O N = A R N, each being a

right angle, while the angle R N O is common to both triangles, therefore[2] the third angle N R O = R A N, that is, the first angle of refraction is equal to half the refracting angle of the prism. But as this angle is known, or may readily be measured, the first angle of refraction is also known; and the angle of incidence being given, the index of refraction is determined, as was formerly explained (§ 28), by dividing the sine of the angle of incidence by the sine of the angle of refraction.

The refractive power, then, of any solid body may be measured, (§ 26, 27), by shaping it into a prism, and of any soft or fluid body, by placing it in the angle of a hollow prism, transmitting a ray of light through the prism in the manner above described, and observing the position when the image of the luminous body has the least deviation. Then dividing the sine of the angle of incidence by the sine of half the refracting angle of the prism, the quotient will be the index of refraction of the substance tried, whatever be the extent of the refracting angle.

On the supposition that the luminous object is at a finite distance, to obtain the amount of the angle of incidence when the deviation is a minimum, we must first measure accurately the angle R′ H′ H, formed by a direct ray, H H′, from the object, and the ray D H′ from the image. This may be done by Hadley's quadrant, the theodolite, or the repeating circle. Supposing the angle R′ H′ H determined, the angle of incidence, H R M, may be found, thus:—Since the angle H = R′ H′ H, and H = X R H, being alternate angles, and N R O = M R X, the whole incident angle is equal to the angle R′ H′ H + O R N or R′ H′ H + C A F. Hence to find the angle of incidence, we have only to add the angle R′ H′ H to C A F, half the refracting angle.

Were the luminous object at an infinite distance, as the sun or a star is generally reckoned to be in such experiments, then the direct ray, S H′, from the object, would be parallel to H R, the incident ray, and the angle S H′ R′, which the refracted ray would make with the direct ray, would be equal to the angle H′ E G, the whole deviation. The half of this angle is equal to E R O, the first deviation, or to its vertical angle H R X, and the remaining part, X R M, of the angle of incidence, to

half the refracting angle. The whole angle of incidence is consequently equal to half the angle S H′ R′ + C A F, half the refracting angle. Hence, to obtain the amount of the angle of incidence, according to this method, we require only to measure the angle S H′ R′, which the direct ray from the sun forms with the refracted ray R′ H′.

Such was the method employed by Newton; only, from his employing the plummet quadrant, instead of taking at once the whole angle S H′ R, he measured separately the sun's altitude H H′ S and the inclination H H′ R of the emergent beam to the horizon.[3]

In measuring the refractive power of fluids, Newton employed a wooden prism, in the sides of which he bored holes, which, he states, he then closed with pieces of a broken looking-glass. Biot,[4] for the same purpose, bores a hole through the sides of a solid glass prism, and covers the apertures by the application of plates of glass. The fluid is introduced through another hole in the base, communicating with the former; a pencil of light is then transmitted, and the refraction measured. A simple hollow prism may be made by fixing together, at any determinate angle, two pieces of plate glass. A portion of the soft or fluid body to be tried is then to be placed in the angle.

§ 39. *Refractions at spherical surfaces reducible to refractions at plane surfaces.*

Lenses, as well as bent glasses, have one or other, or both surfaces, convex or concave. The consequence is that the greater number of the refractions, which become the object of consideration in the science of optics, take place at curved surfaces. The curvatures of glasses and lenses, though generally spherical, may be elliptical, hyperbolical, or parabolical; but the difficulty of grinding these last forms, prevents them from being much employed. The refractions effected in the eye take place wholly at curved surfaces. The circumstance, however, of a refracting surface being formed by a curve, adds no difficulty to the subject, for, as every

curved surface may be regarded as composed of an infinite number of plane surfaces, the refraction which happens at a curved surface of any kind, is exactly the same as at a plane surface touching the curved surface at the point on which the ray falls.

The method of construction, already given (§ 35) for rays refracted at a curved surface, appears the most applicable in practice. When the surface is spherical, it at once furnishes us, at the point of incidence, with the radius of curvature of the refracting surface, which is the perpendicular from which the angle of incidence is to be reckoned, thus rendering the consideration of the tangent to the refracting surface at the same point unnecessary.

§ 40. *Refraction by a bent glass, or curved medium with parallel surfaces.*

If two surfaces, M M′, N N′, fig. 38, the one convex and the other concave, are concentric, like those of a watch-glass, or the cornea, they will act on light like a plane glass, only when the incident rays fall at equal angles on each surface.

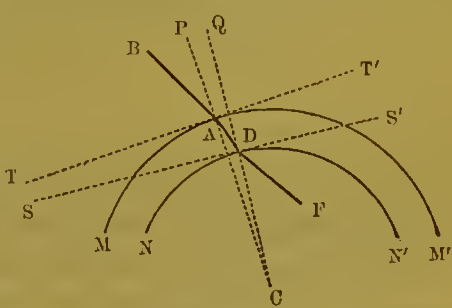

Fig. 38.

If a ray from air falls perpendicularly on A, it will undergo no refraction, but will proceed directly towards the common centre C. If an oblique ray B A is incident at A, it will be refracted into the direction A D, inclined towards P C, a perpendicular to a tangent T T′ at the point A; and on arriving at D, it will be refracted in the direction D F, from the perpendicular Q C to the tangent S S′, at the point D. The emergent ray D F would be parallel to the incident ray B A, provided the tangent S S′ at the point D were parallel to the tangent T T′ at the point A, but this cannot be the case, as these tangents are perpendicular to different radii, C D, C A, and may be compared to the two inclined surfaces of a prism.

In proportion as the incident point A and the emergent point D are nearer to each other, or, in other words, as the medium is thinner, the emergent ray will obviously be more nearly parallel to the incident ray.

Parallel rays falling on the convex surface of a bent glass, diverge slightly from each other, on quitting its concave surface; falling on its concave surface, they converge slightly towards each other, on quitting its convex surface. A myopic eye, therefore, sees a little better on looking through a watch-glass with its convex side towards the object, while a presbyopic eye derives about the same benefit when the glass is turned in the opposite direction.

If a myopic eye looks very obliquely through a watch-glass, with either the convex or the concave side towards it, vision is improved, owing to the divergence which the oblique rays undergo. A ray proceeding from A, fig. 39, will reach the

Fig. 39.

eye at E as if it proceeded from B; and, following the general optical law that the visibility of two points from one another is mutual, a ray from E will reach the eye at A as if it proceeded from C. A presbyopic eye derives no advantage from using a bent glass in this way.

§ 41. *Refraction by a sphere.*

1. *Parallel rays.* Let C, fig. 40, be the centre of a sphere

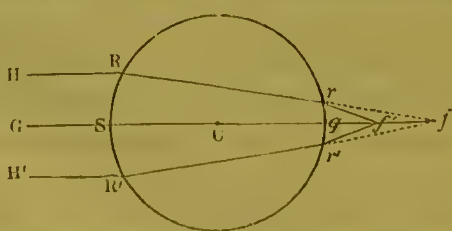

Fig. 40.

of glass, whose index of refraction is 1.5, and let parallel rays, H R, H′ R′, fall upon it at equal distances on each side of the axis, G C *f*. It will be found by construction (§ 35), that R *r* is the course of the ray H R as refracted by the first surface of the sphere; and, in like manner, R′ *r*′ is the refracted ray corresponding to H′ R′.

If we continue the rays R *r*, R′ *r*′, they will meet the axis at *f*, the focus of parallel rays for a single convex surface R S R′. Beyond *f*, the rays would diverge.

The principal focus (§ 4) of a single convex surface may be found by the following rule, whatever be the substance:—Divide the index of refraction by its excess above unity, and the quotient will be, S *f*, the principal focal distance; the radius of the surface, or C S, being 1. If the focal distance is more or less than 1 radius, we must multiply the quotient by the length of the radius, and the result will be the focal distance in the same denomination as that in which the length of the radius is expressed. Thus, to find the focal distance of a convex surface of glass whose radius is 4 inches, we divide 1.5, the index of refraction, by .5, the difference between the index of refraction and unity; and 3, the result, is the focal distance, the radius being supposed unity; now multiplying 3 by 4 inches, we obtain the focal distance in inches, viz. 12. Hence it appears that when the surface is glass, the focal distance, S *f*, is equal to thrice the radius, C S.

Tracing, by construction, the ray R *r*, as it quits the second surface of the sphere, it will be found refracted into the direction *r f*′. In the same manner, we shall find *r*′ *f*′ to be the refracted ray corresponding to the incident ray R′ *r*′, *f*′ being the point where the two rays, by their second refraction, intersect each other and the axis G *f*. Hence the point *f*′ will be the focus of parallel rays for the sphere of glass. Beyond *f*′, the rays would diverge.

The distance of the principal focus, *f*′, from the centre, C, of any sphere, may be found by dividing the index of refraction by twice its excess above 1; the quotient is the distance, C *f*′, in radii of the sphere. For example, if the radius of the sphere is 1 inch, and its refractive power 1.5, C *f*′ will equal 1½ inches, and *q f*′ ½ an inch.

2. *Diverging rays.* If diverging rays fall upon the points R R′, their focus will be at some point of the axis G′*f*, more remote from the sphere than *f*′, the distance of their focus increasing as the radiant from which they diverge approaches to the sphere. When the radiant point is as far before the sphere as *f*′ is behind it, then the rays will be refracted into parallel directions, and the focus be infinitely distant. If we supposed *f*′ *r*, *f*′ *r*′ to be rays diverging from *f*′ and falling upon the sphere, they will emerge after the second refraction in the parallel directions R H, R′ H′.

3. *Converging rays.* If converging rays fall upon the points R, R′, their focus will be at some point of the axis G *f*′, nearer than its principal focus *f*′; and their convergency may be so great that their focus may fall within the sphere.

As the focal distance of a sphere depends on its refractive power, it will vary according to the material of which the sphere is formed. The following are the indices of refraction and the corresponding focal lengths of spheres, of an inch in radius, of four different substances:—

	Index of Refraction.	Length of *q f*′.
Tabasheer, . . .	1.11145	Nearly 4 inches.
Water, . . .	1.3358	Nearly 1 inch.
Glass, . . .	1.5	$0\frac{1}{2}$ —
Zircon, . . .	2.	0 —

In the last-mentioned substance *r* and *f* coincide with *q*, after a single refraction at R. When the index of refraction is still greater than 2, as in diamond and several other substances (§ 29), the point *f* will fall within the sphere. Under certain circumstances, as Sir David Brewster observes,[5] the ray R *r* will suffer total reflection (§ 34) from *r*, towards some other part of the sphere, where it will again suffer total reflection, being carried round the circumference of the sphere, without the power of making its escape, till it is lost by absorption.

§ 42. *General facts respecting the axis, optical centre, and classes of lenses.*

1. The *axis* of a lens is a line, A *a*, fig. 41, joining the centres of curvature of its two surfaces; or, if the lens be plano-convex or plano-concave, it is the perpendicular falling from the centre of curvature upon the plane. A ray of light coinciding with the axis of any ordinary lens suffers no refraction, but other rays suffer an amount of refraction, which increases in proportion to their distance from the axis.

2. In every lens, or in its axis, there is a point, called the *optical centre*, so situated that all the rays which pass through it, take, on quitting the lens, a direction parallel to that in which they entered it.

If two radii, A B, *a b*, fig. 41, be drawn parallel to one another, from the centres of curvature, A *a*, of the surfaces of any lens, L L, and *b* B be drawn cutting the axis in C, C is the optical centre. The incident portion D *b* of a ray passing through C, and B E its emergent portion, are parallel, for the ray, as if it had passed through two parallel planes, is equally refracted at the points *b* and B, and the whole course of the ray is regarded as if it formed one straight line, from which it differs insensibly when the lens is thin.

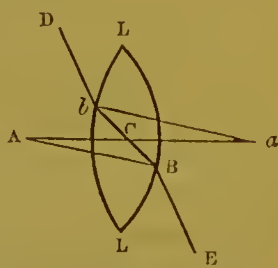

Fig. 41.

In double-convex and double-concave lenses, the optical centre lies within the lens, and nearer to the more curved surface, if the two are unequal; in a plano-convex or plano-concave, it is at the convex or concave surface; in a meniscus, and in a concavo-convex lens, it lies out of the lens, and nearer to the more curved surface; in a sphere, it is at the centre. No practical inconvenience results from supposing it to be always situated within the lens, especially when the thickness is inconsiderable.

3. It has already been explained, (§ 38), that when a ray of light passes through a prism, denser than the surrounding

medium, the total deviation of the ray is in all cases from the vertex. The general effect of any lens may be understood by resolving it into two prisms. If the bases of the prisms, of which the lens is supposed to be formed, be turned towards each other, the lens must be convex, and the total deviation of the rays which pass through it will be towards its axis; but if the bases are turned from each other, the lens must be concave, and the rays of light will be bent from its axis. The rays of light A B, fig. 42, are refracted by the

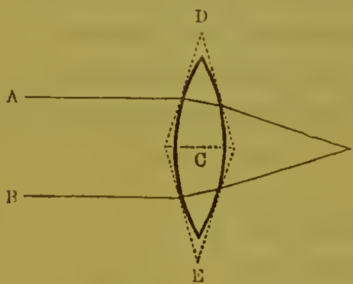

Fig. 42.

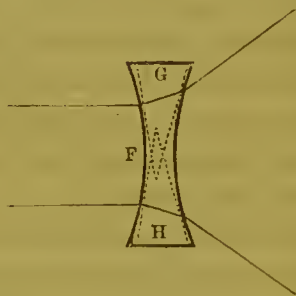

Fig. 43.

convex lens C, as they would have been by the circumscribing double prism D E; and in the same way the concave lens F, fig. 43, resembles in its operation the inscribed prisms G and H.

On this principle, the six lenses, G, H, I, and K, L, M, fig. 34, form two *classes;* the first three being *convergent*, and the last three *divergent.* The first three either cause all the rays to converge, or lessen their divergence, and the last three either cause them to diverge, or lessen their convergence. The lenses which are thinner at the edge than in the middle are convergent, and those which are thicker at the edge than in the middle are divergent. The first class are sometimes called *magnifying glasses*, and are used by those whose eyes have become presbyopic; the second class are called *diminishing glasses*, and serve to aid the vision of those whose eyes are myopic.

What has already been said (§ 38) regarding the non-emergence of rays, falling on the second surface of a prism at an incident angle greater than the critical angle, applies to lenses.

The conditions, also, upon which the course of the rays

which do emerge depends, or, in other words, the distance of the foci of different kinds of lenses, are quite analogous to those which affect the course of a ray emerging from a prism; viz., the refracting power of the substance of the lens, the curvature of its surfaces, and the obliquity of the incident rays.

§ 43. *Refraction by convergent lenses.*

Unless where the contrary is mentioned, the following statements refer to lenses of crown glass.

1. *Parallel rays.* Parallel rays, such as R L, R′ L′, fig. 44, falling on a double-convex lens, being refracted towards the perpendicular at their incidence and from the perpendicular at their emergence, will be so converged by the two surfaces as to meet the axis at F, the *principal focus*, which if the lens is equiconvex, is at a distance behind the lens equal to the radius of either of its surfaces.

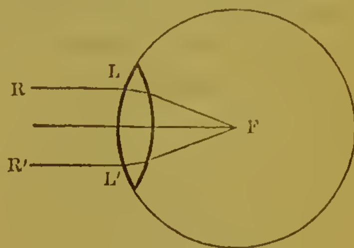

Fig. 44.

If the plane side of a plano-convex lens, fig. 45, is exposed to parallel rays, R L, R′ L′, these are refracted only on quitting its convex surface, and are brought to a focus F, at a distance from that surface equal to its diameter. If the convex side is exposed to parallel rays, R L, R′ L′, fig. 46, these are refracted by both surfaces, and the consequence is that the focal length, Cf, is less than the diameter of the convex surface by two-thirds of the thickness of the lens.

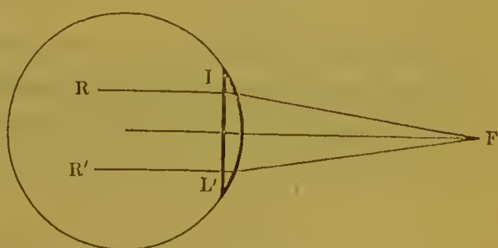

Fig. 45.

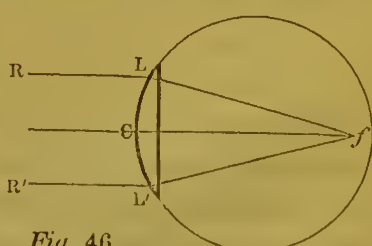

Fig. 46.

If the radii of the surfaces of a double-convex lens are unequal, the effect is the same as if the radii were each

equal to the harmonic mean between them, which is found by dividing their product by half their sum; or, in a meniscus, by half their difference. Thus, were one of the radii two inches, and the other six, the effect would be the same as that of a lens of three inches radius; and if it were a meniscus, the same as that of a lens of six inches.

The focal length of a lens of flint glass, of water, or of any other substance, may be found, by dividing that of an equal lens of crown glass by twice the excess of the index of refraction above unity. Thus the index for water being $1\frac{1}{3}$, we must divide the radius by $\frac{2}{3}$, or increase it one half, for the principal focal distance of a double-convex lens of water.

2. *Diverging rays.* When a radiant point, R, fig. 47, is at twice the distance of the principal focus from a double convex lens, the focus of the diverging rays, R L, R L′, is at an equal distance F, on the other side of the lens.

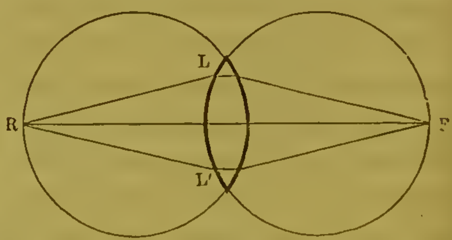

Fig. 47.

When the radiant point recedes farther from the lens than this, the focus becomes nearer; and *vice versa.* The distance of G, the focus of diverging rays, fig. 48, from the principal

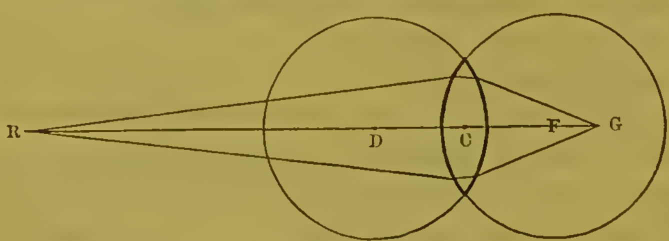

Fig. 48.

focus behind the lens, is always inversely as the distance of the radiant point, R, from the principal focus before the lens. Let D be the principal focus before the lens, F the principal focus behind it, and C the centre, then R D is to D C, as C F is to F G. As the place of G varies with that of R, these two points are called *conjugate foci*, and the two are so related.

that if G becomes the radiant, R will be the focus of refracted rays. Every lens has only one principal focus, but its conjugate foci are innumerable.[6]

If R, approaching the lens, came to D, so that the incident rays issued from a body situated in the principal focus of the lens, the focus of the refracted rays would be infinitely distant, or, in other words, they would become parallel. If R approached the lens still more, so as to be between D and C, the refracted rays would diverge, and have a virtual focus before the lens.

If R recedes from the lens so as to be infinitely distant from it, G will coincide with F, for the rays falling on the lens may then be considered parallel.

3. *Converging rays.* When rays, converging to a point, as R G, R′ G, fig. 49, fall upon a double-convex lens, they will be so refracted as to converge to a focus, *f*, nearer to the lens than its principal focus, F. If the point of convergence, G, recedes from the lens, the focus *f* will also recede from it towards F, which it just reaches when G becomes infinitely distant, or, in other words, when the incident rays become parallel. If G approaches the lens, *f* also approaches it. G and *f* are conjugate foci.[7]

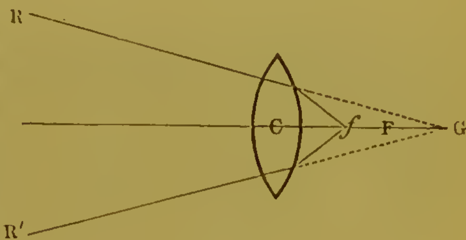

Fig. 49.

§ 44. *Refraction by divergent lenses.*

All that has been said of convex lenses may be applied directly to concave, if we only substitute divergence for convergence.

1. *Parallel rays.* If R L, R′ L′, fig. 50, be parallel rays incident upon a double-concave lens, they will diverge after refraction in the directions L *r r*, L′ *r r*′, as if they radiated from F, the virtual focus of the rays L *r r*′, L′ *r r*′, and the principal focus of the lens.

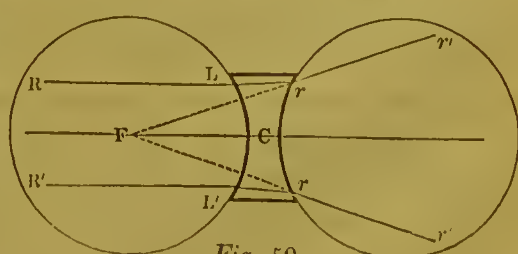

Fig. 50.

The principal focal distance, C F, is the same as in convex lenses. When the lens is unequally concave, the focal distance will be found by the rule for unequally convex lenses.

2. *Diverging rays.* When the lens, L L′, fig. 51, receives

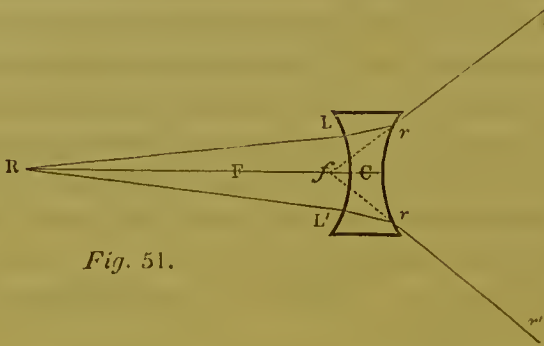

Fig. 51.

the rays R L, R L′, diverging from R, without the principal focus, they will be refracted into lines, L r r', L′ r r', diverging from a virtual focus, f, nearer the lens than the principal focus, F. As R approaches to C, f will also approach to it, and the distance R C, or f C, will be found, when either of them is given, by the same rule as for diverging rays falling upon convex lenses.

3. *Converging rays.* When rays converge with such a degree of obliquity as R L, R′ L′ fig. 52, towards a point f, beyond the principal focus, F, of a concave lens, they will be refracted into the directions L N, L′ N′, so as to have a virtual focus at F″, in front of the lens, and beyond its principal focus, F′. When f coincides with F, the refracted rays will be parallel; and when f is within F, the refracted rays will converge to a focus on the same side of the lens with f, but farther from the lens. The foci, f and F, are conjugates, and when the position of one of them is given, that of the other

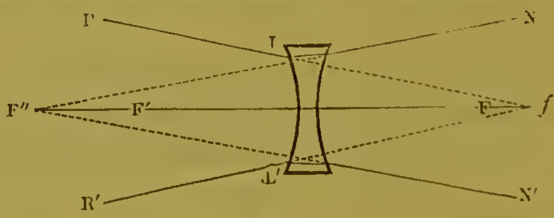

Fig. 52.

may be found by the rule for converging rays falling on convex lenses.

The general effect of a concavo-convex lens, in refracting parallel, diverging, and converging rays, is the same as that of a concave lens of the same focal length. The rules for finding the foci are the same as those for a meniscus.

§ 45. *Formation of images by convergent and divergent lenses.*

We have already referred (§ 23), but only in a very general way, to the formation of images by a double-convex lens. It is necessary that we should now resume the subject of the formation of images by refraction, and especially by that of convergent lenses.

In the last two sections, the foci of lenses have been considered only in relation to a single pencil of parallel rays, a single radiant point in the axis of the lens, or rays converging towards the axis. It is equally necessary to attend to pencils of rays, and to radiant points, situated out of the principal axis; for when an image of any object is formed by refraction, the light emanates from a great number of radiant points, placed in various directions.

Let the student take a double-convex lens, such as a common reading glass, or the glass of a pair of convex spectacles, and make himself familiar with the six following experiments. In order to understand them thoroughly, he should construct a diagram illustrative of each, as he proceeds.

1. If the lens is held close to a lighted candle, and of course within its principal focal length, the diverging rays, by traversing the lens, suffer some diminution of divergency, but not a sufficient diminution to enable them to form an image of the candle on the opposite wall of the room, or on a screen, whatever be the distance at which the screen is placed.

2. If the lens is now moved slowly from the candle, towards the wall, the circle of diverging light is first of all observed to become proportionally contracted; the light is then seen to change its circular form, and assume an elongated form; and

as we proceed, it speedily brightens into a magnified and inverted image of the candle. The lens is now at its principal focal distance from the candle. The enlarged size of the image shows that though the divergency of the light has become greatly less than in the first experiment, it still diverges. Each point of the luminous object sends out a pencil of rays, and these rays, we know, are now proceeding parallel to each other, for they issue from the situation of the principal focal distance of the lens; but, though the rays are parallel, the pencils are still diverging, else the image could not be larger than the luminous object which it represents.

3. If we move the lens still more towards the wall, the magnified and inverted image first of all changes into a dim circle of light; this in its turn disappears, and one who had not made himself acquainted with the fact, would say that a dark shadow of the lens was now formed on the wall, surrounded by a broad halo of light. As we proceed with the lens towards the wall, light seems at length to penetrate through the lens, and at the same time the halo round its shadow becomes more evident. The light increases in brightness as the lens approaches the wall, and when it has reached the distance of its principal focus from it, a small, inverted, and distinct image of the candle appears, surrounded by a circle of perfect darkness, equal in diameter to that of the lens. The rays forming each pencil issuing from the candle, as well as the pencils themselves, may, in this position of the lens and image, be regarded as parallel. By the refractive power of the lens, they are converged to focal points, and hence the smallness, vividness, and distinctness of the image.

In this experiment, the disappearance of the image as the lens is moved from the candle, and the substitution of what seems a dark shadow of the lens, are too remarkable not to excite inquiry. The darkness of the shadow is not real. If we repeat the experiment, with the lens exactly inserted into a round hole in a sheet of pasteboard, the surrounding part of the wall being thereby shaded, we shall readily perceive the circle of light which is transmitted through the lens, instead of the appearance of a dark shadow as before. Let

R L, R′ L′, fig. 53, represent rays incident from the candle on

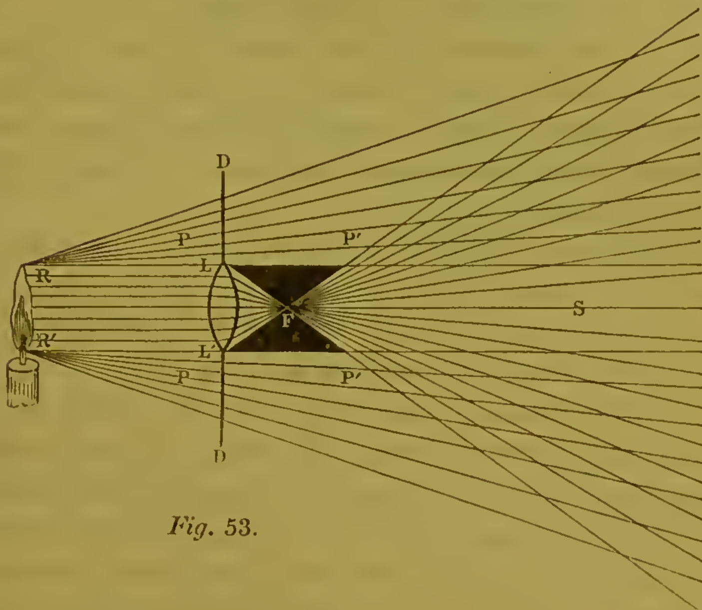

Fig. 53.

the lens. They will be converged to a focus, F, after which they will again diverge, and mingling with the rays, P P′, P P′, which flow past the lens on all sides, will form the halo of light already mentioned. Immediately around the focus there is no light. In a straight line behind the focus there is so little light, that when contrasted with the luminous halo formed by the diverging rays from the focus mingling with the rays which flow past the lens, a dark shadow of the lens seems to be formed on the wall, at S. By cutting off the lateral light by means of the pasteboard diaphragm, D L, D′ L′, we darken comparatively the space directly behind it, and are thus able to show the faint light at S, which is transmitted by the lens, and diverges from F.

This experiment affords a good illustration of a remarkable property of vision, namely, the comparative intensity of our impressions according to the contrast of light and darkness. The same quantity of light, which, transmitted through the lens without the diaphragm, we are disposed, from its contrast with the surrounding brightness, to call dark, we discover to be comparatively bright, when the diaphragm circumscribes it with a shadow. The value of light, then, in reference to

its effect on the eye, is not always in the ratio of its actual intensity, but depends much on the manner in which it is contrasted with surrounding light of greater or less brightness. This is the reason why the flame of a candle is scarcely discernible in broad daylight; and why the stars become visible at different times after sunset, according to their different degrees of brightness.

4. In the above experiments, the luminous body and the wall or screen have remained at the same distance from each other. If we bring the candle towards the wall, so that it is at the distance from it of four times the focal length of the lens, and if we place the lens midway between the candle and the wall, a distinct inverted image will appear, of the same size as the luminous body. The rays diverging from each luminous point of the candle are in this case brought by the refractive power of the lens, to a corresponding focal point on the wall. Fig. 47, serves to illustrate this experiment; R, representing a luminous point of the candle, and F the place of the image of that point.

5. If we now bring the lens nearer to the wall by one half its focal distance, and place the candle at thrice the focal distance from the lens, an inverted image will appear, smaller than the object. If we place the lens at $1\frac{1}{3}$ its focal distance from the wall, to obtain a distinct image we will require to move the candle from the lens to four times the focal length.

6. An inverted image, larger than the object, will be obtained by removing the lens from the wall to thrice its focal distance, and placing the candle at $1\frac{1}{2}$ the focal distance from the lens: Also, by placing the lens at four times its focal length from the wall, and the candle at $1\frac{1}{3}$ the focal length from the lens.

Experiments 5 and 6 illustrate the motions and relations of the conjugate foci of diverging rays; F G, fig. 48, varying reciprocally as D R, that is, increasing in the same proportion as D R diminishes, and diminishing in the same proportion as D R increases.

These experiments, then, being repeated and understood, some farther explanations are necessary regarding images formed by refraction.

Let A B C, fig. 54, represent an object placed farther from

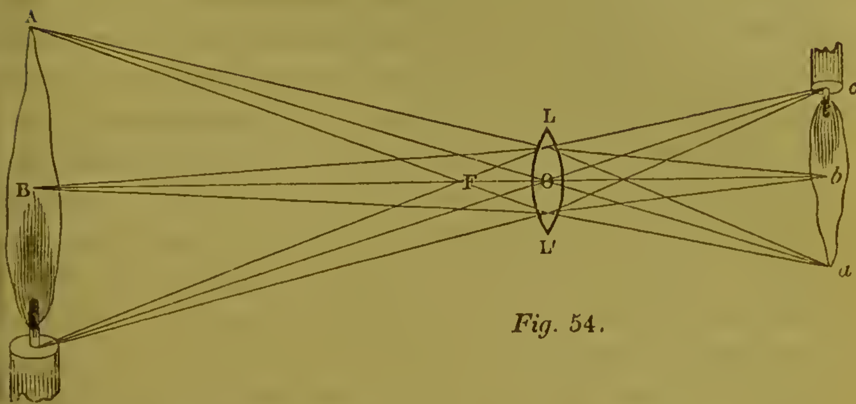

Fig. 54.

a convergent lens, L L′, than its principal focal distance, F. Cones of diverging rays, flowing from every point of the object, will fall on the surface of the lens, and being refracted by it, will be converged into as many corresponding points, behind the opposite surface, where an image of every point will be formed, and consequently an image, *a b c*, of the whole object. The cone of diverging rays, A L, A L′, flowing from the point A, will form a cone of converging rays, the apex of which will be at *a*, and will there form an image of the point A; the rays, B L, B L′, will be united by the refractive power of the lens at *b*, and will there form an image of B; the rays, C L, C L′, flowing from C, will be united at *c*, where they will form the image of C; and so on, of the whole infinity of intermediate points between A and C.

The incidence upon the lens of such a ray as B *b*, is *direct;* that of A O, or C O, is *oblique* and *centrical;* that of A L, B L, or C L, is *oblique* and *eccentrical.* The *direct* ray suffers no refraction. The rays which are *oblique* and *eccentrical* must evidently be considerably bent, or emerge in a different direction from that of their incidence, in order to be collected into focal points; while those which are *oblique* and *centrical,* from the portions of the two surfaces of the lens by which they are refracted being nearly parallel to one another, proceed in their original direction, or in a direction parallel to it, so that these rays serve to indicate the track in which the image of each radiant point is to be found. It has already

been stated (§ 42), that all the rays which pass through the optical centre of a lens proceed, without sensible error, in the same straight line, which is therefore called a *secondary axis.* The image of any radiant point, out of the principal axis of the lens, will be found in the course of one of its secondary axes. The upper end, A, of the object will be represented where the secondary axis, A O *a*, is intersected by the rays L *a*, L′ *a*; and the lower end, C, where the line C O *c* is intersected by the rays L′ *c*, L *c*. The line joining A *a*, passes through O, the centre of the lens; and the same thing is true of the line joining any of the other corresponding points of the object and image. As the rays cross at O, the image is inverted, and subtends at O an equal angle, *a* O *c*, to that which the object subtends at the same point on the other side, A O C.

If a screen be placed at *a b c*, the image of the object will be visible on the screen. The student has been trying the experiment with a candle, throwing its image on the wall; he may repeat it at a window, when the forms of external objects, the houses, trees, &c. will be pictured on the screen, forming there a miniature of the utmost brilliancy and fidelity. If the screen be semitransparent, the picture may be seen by an eye placed behind it, as well as by one in front of it. We may remove the screen, and the image will still be seen, even more distinctly, as if a real object, not a mere picture, were before us.

Any radiant point, such as A or C, not in the axis of a lens, has in general its image at a less distance behind the lens than such a point as B, which is situated in the axis; but the difference is too small to be sensible in common cases. We may, therefore, suppose the image of any oblique point to be at the same distance as if it were direct, or to be in a plane crossing the axis perpendicularly at that distance, so as to form part of a flat image, of which the magnitude is determined by straight lines drawn from the extremities of the object through the optical centre of the lens. This is, however, an approximation, which is admitted only for the greater convenience of computation and representation, the image being generally curved. If the object is a spherical segment, concentric with the lens, and the angle subtended by it at O is

small, the image does not differ sensibly from a similar segment. If the object is a straight line, the image is the arc of a conic section, the curve being an ellipse, parabola, or hyperbola, according as B O is greater than, equal to, or less than F O. At its vertex, *b*, the curvature of the image is the same, wherever the object is placed. From all this it follows, that the image of any object, received on a plane screen, must to a certain extent be distorted and confused towards its edges.

With a convergent lens, we are able to form an image, at any distance behind the lens, greater than its principal focal length, and in any proportion to the object. To have the image large, we bring the object near the lens; to have it small, we remove it from the lens. In the two triangles, A O C, c o *a*, the *linear* magnitude of the image, *c a*, is to that of the object A C, as the distance of the image, o *b*, is to O B, the distance of the object, from the lens. The *absolute* magnitude of the image: the absolute magnitude of the object : : o b^2 : O B^2. In other words, the area of the image varies as the square of its distance. It has already been stated (§ 12) that the same ratio exists between the object and its image formed by radiation, but in this case the aperture of transmission must, like the optical centre of a lens, be supposed a mathematical point.

The size of the image is not influenced by the size of the lens or the area of its surfaces, provided the focal length is the same, but only the brightness of the image.

It is a general rule, that when an image is formed by any lens, if the rays which pass through it converge, as is represented in fig. 54, to actual foci, the image is inverted. The inverted image is smaller than the object, whenever the object is at a greater distance than twice the principal focal length; larger, when the object is within this distance.

It is another general rule, that when an image is formed by any lens, if the rays diverge from a virtual focus, and the object and image subtend equal angles at the centre of the lens, the image is erect. This is the case, for instance, when we look through a convex lens at the letters of a book, so as to see them magnified. The letters form the object, they are

placed within the principal focal length, and by looking at them through the lens, we see a virtual, erect, and magnified image of them. This we shall explain more fully when we come to the subject of vision aided by art, as well as the fact that divergent lenses always form a virtual image, which is erect and smaller than the object.

§ 46. *Experimental determination of the focal length of lenses.*

1. *Convergent lenses.* *α.* Several of the experiments referred to in the last section, afford the means of determining the focal length of lenses. For instance, as in experiment 4, a lighted candle may be placed at one end of a graduated scale of inches, such as a carpenter's rule, and a piece of card set up at the other end, at right angles to the scale. The lens to be tried, being always kept between the light and the card, these are to be moved, until it be ascertained what is the least distance between them at which a clear image is formed. That distance is four times the focal length.

β. Place the lens between any object, as a window in the day or a candle in the night, and the wall or a screen, and move the lens backward and forward till the image appears most distinct. Measure the distance of the lens from the object, and also from the image. Multiply them together, and divide their product by their sum; the quotient will be the focal length. Or, divide the square of the distance of the observed focus, by the distance of the object from this focus, and this will give the excess above the principal focal length.

γ. The sun is so distant, that the rays, proceeding from any point of his surface, may be regarded as parallel; and the principal focal distance of a surface or substance may be practically determined by measuring the distance of the image of the sun, formed by it. To find the focal length, then, of any convex lens or meniscus, hold it in the sunbeams, so that the rays may fall on one of its surfaces perpendicularly, and move it backward and forward till the rays are collected on a screen into the smallest white round spot. The spot is the

image of the sun, or solar focus, and the distance between it and the lens is the focal length.

δ. Having covered either side of the lens with pasteboard, in which there are small holes made with a pin, expose the lens directly to the sun. The rays which pass through the holes will appear as so many white spots upon a screen held behind the lens; and these spots will come closer together, as the screen is drawn back from the lens, till at last they unite in one spot or focus. The distance of this focus from the lens may then be measured. It will not be sensibly altered by inclining the lens a little to the incident rays, provided this small inclination be so made as not to move the optical centre of the lens. If the screen be drawn farther from the lens, the spots will recede from each other.

2. *Divergent lenses.* α. If a concave lens, covered in like manner, be exposed to the sun, the spots of light which come through the holes and fall upon the screen, will continually recede from each other as the screen is moved from the lens, showing that the emergent rays diverge from a virtual focus situated before the lens. When the distance of any two spots from each other is double that of the two corresponding holes in the cover through which they come, the distance between the screen and the lens is equal to the principal focal length.

β. The same experiment is varied a little by cutting a round hole in a piece of black paper, and laying it on the lens with gum water, so that the centre of the hole may be in the middle of the lens; striking a circle on a screen, with a radius equal to the diameter of the hole on the lens; holding the lens in the sunbeams, and moving the screen backward and forward, till the rays diverge so much as just to fill its circle. The distance between the lens and the screen is then equal to the distance of the virtual focus from the lens.

γ. Let the concave lens be placed in contact with a convex lens whose focal length is known, and determine the focal distance of the combination experimentally. Then, divide the product of these focal distances by their difference, and the quotient is the focal length of the concave lens.

[1] Euclid, Book i. Prop. 15 and 32.

[2] Ib. Prop. 32.

[3] Newton's Optical Lectures, 19, 57, 67; London 1728.

[4] Précis Elementaire de Physique Expérimentale, ii. 121; Paris 1817.

[5] Treatise on Optics, 37; London 1831.

[6] The following rules for finding the foci of glass lenses, by numerical calculation, are taken from Martin's System of Optics; London 1740:—

To find the focus of diverging rays, if the lens is *equiconvex,* multiply the distance of the radiant, R C, fig. 48, by the radius of convexity, and divide the product by the difference of the said distance and radius; the quotient will be the distance of the focus, C G.

If *unequally convex*, multiply twice the product of the radii of its surfaces by the distance, R C, for a dividend. Multiply the sum of the radii by the same distance, and from this product subtract twice the product of the radii for a divisor. Divide the above dividend by the divisor.

If *plano-convex,* take twice the product of the radius by the distance of the radiant point, and divide it by the difference between that distance and twice the radius.

If a *meniscus,* multiply twice the distance of the radiant by the product of the radii for a dividend. Multiply the difference of the radii by the same distance, and to this product add twice the product of the radii for a divisor. Divide the above dividend by this divisor.

[7] The conjugate focal distance C *f*, fig. 49, may be found by the following rules:—

If the lens is *equiconvex*, multiply the principal focal distance, C F, by C G, the distance of the point of convergence, and divide the product by the sum of the same numbers; the quotient will be the distance C *f*.

If *unequally convex*, multiply twice the product of the radii by the distance C G, for a dividend. Multiply the sum of the radii by the same distance, and to the product add twice the product of the radii, for a divisor. Divide the above dividend by the divisor.

If *plano-convex,* divide twice the product of the distance C G, multiplied by the radius, by the sum of that distance and twice the radius.

If a *meniscus,* the same rule is applicable as for diverging rays.

CHAPTER VII.

REFRACTIVE POWERS OF THE LENSES OF THE HUMAN EYE.

§ 47. *Lenses of the human eye.*

Optical instruments which operate on light by refraction are called *dioptric* instruments, from δια, *through*, and ὀπτομαι, *I see*.

The eye is a dioptric instrument; that is to say, it operates on light by refraction. We have already (§ 9) noticed the comparison of the eye to a *camera obscura*, an instrument (fig. 10) which does not necessarily operate by refraction, but which is improved by the addition of a dioptric contrivance, viz. a convergent lens.

The eye, however, is supplied with more than one lens. The dioptric parts of this organ are four, viz. the cornea, the aqueous humour, the crystalline lens, and the vitreous humour; and, unless changed by age or by disease, they are perfectly transparent and free from colour. (§ 2).

The cornea, (2, fig. 3) taken singly, is generally regarded as a segment of a hollow sphere, or as a curved medium bounded by parallel surfaces, (§ 40), like a watch-glass.

The aqueous humour (11, 10, fig. 3) approaches to the form (I, fig. 34) of a meniscus. It is truncated at its circumference, and is partially divided by the iris, (7, fig. 3), as by a diaphragm.

The crystalline (9, fig. 3) is a very thick double-convex lens. If we may be allowed to speak of its surfaces as spherical, the posterior surface is a segment of a smaller sphere than the anterior, and therefore considerably more convex. The edge, in which the surfaces should meet, is rounded off.

The vitreous humour (5, fig. 3) may be considered as a

meniscus, with its concave surface directed forwards. This surface is formed by a segment of a small sphere, while the posterior is a large segment of a large sphere, and is necessarily convex.

To estimate with perfect correctness the dioptric effects of the eye, we would require to possess an exact knowledge of the refractive and dispersive powers, as well as of the curvatures, proportions, and positions of its transparent parts. Many of these points being but imperfectly determined, and some of them scarcely ascertainable, experiment has in many cases been substituted for calculation, and approximations received where certainty could not be obtained, so that the functions of the eye have not yet been explained in all their detail. With regard to the investigation of this organ, it is to be regretted that mathematicians have often been deficient in anatomical knowledge, while anatomists have been unacquainted with the science of optics, and the method of calculating with accuracy the results of their observations.

§ 48. *Dimensions of some parts of the human eye.*

The following are the medium dimensions, and proportions, of some of the parts of the human eye, the curvatures being supposed spherical:—

Axis of eye, (*c d*, fig. 2.) . . .	$\frac{19}{20}$ths	of an inch.
Thickness of cornea, ...	$\frac{1}{30}$th	do.
Axis of anterior chamber of aqueous humour, .	$\frac{1}{10}$th	do.
Axis of posterior chamber of aqueous humour, .	$\frac{1}{50}$th	do.
Axis of crystalline, ...	$\frac{7}{40}$ths	do.
Axis of vitreous humour, rather less than . .	$\frac{12}{20}$ths	do.
Axis of whole transparent media, from vertex of cornea to that of retina, . . .	$\frac{18}{20}$ths	do.
Thickness of retina, choroid, and sclerotica, in axis of eye, ...	$\frac{1}{20}$th	do.
Transverse chord of cornea, ...	$\frac{18}{40}$ths	do.
Vertical chord of cornea, . . .	$\frac{17}{40}$ths	do.
Radius of convexity of cornea, . . .	$\frac{13}{40}$ths	do.
Radius of concavity of cornea, . . .	$\frac{7}{34}$ths	do.

Diameter, or transverse axis, of crystalline, .	$\frac{7}{20}$ths	of an inch.
Radius of anterior surface of crystalline, .	$\frac{13}{40}$ths	do.
Radius of posterior surface of crystalline, . .	$\frac{9}{40}$ths	do.
Aperture of pupil varies .	from $\frac{12}{100}$ths to $\frac{25}{100}$ths	do.
Distance between centres of pupils, . . .		$2\frac{2}{5}$ inches.

§ 49. *Curvatures of the lenses of the human eye.*

The number of curvatures to be determined in the eye is not so considerable as might at first sight appear; for the posterior curvature of the cornea is the same as that of the anterior surface of the aqueous humour, the posterior curvature of the aqueous humour is the same as the anterior curvature of the crystalline, and the posterior curvature of the crystalline the same as the anterior curvature of the vitreous humour. As for the posterior curvature of the vitreous humour, it is of no importance so far as the course of the light through the eye is concerned, but only in as much as it is the same curvature which the retina presents to the images formed within the eye. The greater distinctness of these images, and the greater exactness of the coincident impressions, which in all likelihood result from this part of the organ being curved instead of plane, (§ 45), make it desirable that the curvature were known. Although it is probably an arc of a conic section, it is difficult to ascertain its form by observation; so much so that Chossat, who bestowed much attention on this subject, seems to have abandoned the inquiry in despair, even in regard to the eye of the ox. Treviranus regarded the curvature of the retina in the mammalia as approaching to that of an epicycloid. Were it ascertained what is the curvature of the retina after death, it would still remain doubtful whether in the accommodation of the living eye to different distances, the contraction of its muscles or other causes might not have the power of varying the curvature.

Perfection in vision would require *regular* curvatures in the lenses of the eye; yet there is reason to believe that, in many instances, the curvatures are not perfectly regular. Thus,

double vision with one eye is not unfrequent, and must depend on some deviation from perfect regularity. One of Mr Airy's eyes, from some defect in the figure of its lenses, refracts the rays of light which fall upon it in the vertical plane to a nearer focus than those which fall in the horizontal plane. It is probable that this is owing to the curvature of the cornea in the affected eye being greater in the vertical than in the horizontal direction.[1] There is reason to believe that this conformation of the cornea is not very rare. Its existence may be ascertained by directing the eye to a number of parallel lines, drawn on paper, at the distance of $\frac{1}{20}$th of an inch from one another. When a person finds the distance at which he can perfectly distinguish the lines, placed vertically, let them be turned into a horizontal position, and if his eye has this particular conformation, they will appear confused, and as if running into one another. The lines being placed vertically, their image, in such an eye, is formed on the retina; placed horizontally, it would be formed behind the retina.[2]

It is generally assumed that the curvatures of the lenses of the human eye are spherical; but, for two reasons, it is probable that they are elliptical or hyperbolical. The first reason is, that either of these latter curves, as we shall explain hereafter, would render the images on the retina more exact than those produced by spherical curves. The second reason is analogical, and derived from the structure of the eye in some of the lower animals. As for those authors who have supposed they could discover, simply by sight, that the surfaces of the cornea or of the crystalline present a hyperbolical or elliptical form, such a notion shows only how widely they have miscalculated the matter, and how much they have allowed their imagination to impose on their senses.

1. *Curvatures of the cornea.* Chossat has shown[3] that the cornea of the ox is a segment of an ellipsoid of revolution about the major axis, and Sir John F. W. Herschel,[4] has, from an oversight, applied Chossat's observations to the cornea of the human eye. The surface of the human cornea may be ellipsoidal, or present a surface formed by the revolution of some other conic section, but neither the kind nor the degree

of curvature of the refractive surfaces of the eye of one animal, can be inferred from what exists in another animal. Chossat found the cornea of the elephant to be a hyperboloid.

The true axis of the elliptical arc, represented by the horizontal section of the cornea of the ox, does not fall on the middle of that arc, but, inclining towards the nose, it forms with the perpendicular intersecting the middle of the chord joining the two extremities of the arc of the cornea, an angle of about 10°. The ratio of the major axis of the ellipsoid, of which the cornea of that animal is a segment, is to twice the distance between the foci of the generating ellipse, as 1.3 to 1, which being nearly the same as 1.34, the index of refraction of the cornea, to 1, parallel rays incident in the direction of the axis of the eye of the ox, will converge to a focus behind the cornea, almost with mathematical exactness.

Scheiner[5] regarded it as beyond controversy that the cornea of man was not spherical, and thought it probable that its curvature was that of a parabolic or hyperbolic spheroid, and a similar opinion was entertained by Demours.[6]

If the base of the cornea is not circular, its curvature cannot be spherical. Viewed internally, however, the circumference of the cornea is said to be quite circular, and its diameter the same in every direction, but externally it is evidently encroached upon by the sclerotica above and below, and while towards the nose it appears circular, its outline towards the temple is slightly oval. Its vertical diameter, measured externally, is shorter than its transverse.

The adult human cornea seems to be of equal thickness throughout, although it has been alleged that at birth it approaches to the form of a meniscus, while in old age it tends to become concavo-convex. Krause has lately described the anterior surface of the cornea as spherical, and the posterior as parabolic. It may fairly be doubted, whether the surfaces of the human cornea are such as could be formed by the *revolution* of any curve.

2. *Curvatures of the aqueous humour.* The interior of the eyeball consists of three cells or cavities, filled with media which differ sensibly *inter se* in density. The first of these

media is the aqueous humour. The cell in which it is contained is bounded on its anterior side by the cornea, and posteriorly by the capsule of the crystalline. An ordinary meniscus (§ 35) is formed by two curvatures of which the radii are unequal, but as the radius of the posterior curvature of the cornea is equal to that of the anterior curvature of the crystalline, the aqueous humour differs from a meniscus, to which kind of lens, however, from its general similarity of form, it is commonly referred.

3. *Curvatures of the crystalline.* The figure of the crystalline is a solid of revolution, having its anterior surface much less curved than the posterior. It bears a resemblance to two plano-convex lenses placed in apposition by their plane surfaces; the anterior of the two measuring .07608 of an inch in thickness, and the posterior .09878, thus making the lesser axis, *c d*, fig. 55, of the lens equal to .17486, or about $\frac{7}{40}$ths of an inch, which is one half the length of *a b*, its major axis.

Fig. 55.

A central section of the crystalline exhibits apparently two semi-ellipses, whose common major axis, *a b*, is the whole length of the lens, and whose semi-minor axes, *c*, *d*, are the thicknesses above mentioned. But they may be only segments of ellipses, less than semi-ellipses, having the common base the length of the lens, as the ordinates do not exactly correspond to those of semi-ellipses, but are rather less.

According to Chossat, both surfaces of the crystalline are, in the ox, ellipsoids of revolution about their lesser axes; but it would seem from his measurements that the axes of the two surfaces are neither exactly coincident in direction with each other, nor with that of the cornea, but are both inclined outwards, and contain with each other in the horizontal section in which they lie an angle of 5°. This deviation would be fatal to distinct vision, as is remarked by Sir John F. W. Herschel, were the crystalline very much denser than the other media, or were the whole refraction performed by it. This, however, is not the case; for the mean refractive index of the crystalline is only 1.384, while that of the aqueous humour is 1.337, and that of the vitreous 1.339; so that the whole amount

of bending which the rays undergo at the surface of the crystalline is small, in comparison with the inclination of the surface at the point where the bending takes place; and, since near the vertex, a material deviation in the direction of the axis can produce but a very minute change in the inclination of the ray to the surface, this cause of error is so weakened in its effect, as, probably, to produce no appreciable aberration.

The effect of the elliptical figure of the surfaces of the crystalline of the ox, like that of a similar figure of the cornea, will be to correct the aberration of the oblique pencils of light entering the eye.

I am inclined to think that the axes of the two surfaces of the human crystalline, if not exactly, are very nearly coincident in direction with each other, although not with that of the cornea. I conceive the human crystalline to differ from that of the ox in this, that its surfaces are ellipsoids of revolution about one and the same lesser axis. So far as I can judge from magnified designs of it, taken by means of the magic lantern, the human lens is symmetrical.

Kepler[7] regarded the posterior surface of the crystalline as hyperbolical.

Although Rosas[8] describes the lens in the common way as a double-convex lens, formed of two convex surfaces, he represents the convexity of each surface as diminishing rapidly towards the margin of the lens.

Home represents[9] the posterior surface as suffering a similar diminution in its convexity. Roget copies Home's figure, and says that nature has "given to the surfaces of the crystalline lens, instead of the spherical form, curvatures more or less hyperbolical or elliptical."[10] The figures of Home and Rosas are greatly exaggerated.

§ 50. *Refractive densities of the lenses of the human eye.*

It is necessary to distinguish the refractive power of a substance from the power of a lens. The former is expressed by the absolute or relative index of refraction (§ 28); the latter is dependent on the form, as well as refractive density of the

lens, and is measured by the degree of divergence or convergence of the refracted above that of the incident rays. We have first to direct our attention to the refractive powers of the substances which form the lenses of the eye.

Scheiner,[11] without stating any precise value of the refractive powers of the eye, announced that the aqueous humour differed little from water in this respect; that the crystalline approached to glass; and that the vitreous humour probably possessed a refractive power greater than that of the crystalline. In the last particular, he fell into a serious and unaccountable error.

Hauksbee, Wollaston, Young and others have published statements regarding the refractive powers of the humours; but those of Chossat and Brewster are the most detailed.

According to Wollaston,[12] the index of refraction of the vitreous humour is the same as that of water, 1.336; that of the surface of the crystalline of the ox, 1.380; that of its centre, 1.447; the mean, 1.430; that of the centre of the crystalline of a fish, and of the dried crystalline of the ox, 1.530.

The method pursued by Chossat[13] for ascertaining the refractive powers of the media of the eye was first pointed out by Euler, and consists in forming with the substance to be examined a concave microscopic lens, by pressing it between two glasses, the one plane and the other convex, and then determining by observation the length of the focus of this compound objective, in order to deduce the refractive power. The exactness of the results depends partly on two circumstances; viz. the slight incertitude of the precise focus of a compound microscope, and the variable extent of distinct vision in different observers.

Sir David Brewster[14] introduced the humours one by one into a hollow prism formed by two plane laminæ of glass, fixed at an invariable angle; and that the chance of error might be the least possible, he compared the refractions occasioned by the humours, directly with that produced by water.

1. *Mucus covering the cornea.* Were the cornea allowed to become dry externally, it could not retain its transparency. This inconvenience is prevented by a thin layer of mucus,

secreted by the conjunctiva, which keeps the surface of the eye constantly moist, and aids the office of the cornea by allowing those rays to penetrate which would otherwise be reflected from its surface. The refractive power of mucus is very little more than that of water.

2. *Conjunctiva, or mucous coat of the cornea.* The external surface of the cornea is invested by a membrane which Haller regarded as epidermis. This membrane, though continuous with the conjunctiva, differs from it in this respect, that it coagulates instantly on being exposed to boiling water, becoming at the same time opaque, and presenting the appearance of coagulated albumen, although it is probably composed of gelatine. Chossat states its refractive power in the turkey and the carp to be 1.357, which is superior to that of the aqueous humour in these animals.

3. *Proper substance of the cornea.* The proper substance of the cornea is lamellar. Between the lamellæ, there is a considerable quantity of watery fluid. According to Müller,[15] the cornea, by boiling, is entirely resolved into chondrin, which is a peculiar variety of gelatine, discovered by him, and differing from common gelatine in being precipitated by alum, sulphate of alumine, acetic acid, acetate of lead, aud sulphate of iron.

As it is too dense in most animals to be submitted, in its entire state, to pressure between the glasses, Chossat contented himself with experimenting on separate bits of the cornea. In all such observations, it is important, to preserve the substance which is the subject of experiment in its natural state both of transparency and consistence, allowing it neither to become dry nor to imbibe moisture. Compression destroys the transparency of the cornea. Chossat obtained for the refractive power of the cornea, the following results:—

Man.	Bear.	Elephant.	Ox.	Turkey.	Carp.
1.33	1.35	1.34	1.34	1.35	1.35

These refractive powers differ very little from that of water; which no doubt arises from the fact, that the thickness of the cornea depends in a great measure on the fluid contained in its substance.

4. *Lining membrane of the cornea, or capsule of the aqueous humour.* Chossat determined its refractive power only in the elephant and ox, on account of the difficulty arising from the readiness with which the membrane breaks and rolls itself up. He obtained for the elephant 1.349, and for the ox 1.339.

5. *Aqueous humour.* The aqueous humour weighs from $4\frac{1}{2}$ to $5\frac{1}{2}$ grains. Its speeifie gravity is 10053. It is essentially a weak solution of common salt, much resembling the tears. In the ox, it eontains, according to Berzelius:—

Common salt, with a feeble tracc of an extract soluble in alcohol, . . .	1.15
Extraetive matter soluble only in water, .	0.75
Albumen, a trace, ...	
Water, ...	98.10
	100.00

Chossat's experiments on the aqueous humour of different animals show that it differs very little from water. His results were

Man.	Bear.	Hog.	Elephant.	Ox.	Turkey.	Carp.
1.338	1.349	1.338	1.338	1.338	1.344	1.349

6. *Crystalline capsule.* The anterior crystalline eapsule closely rescmbles, in its physical propcrties, the lining membrane of the cornea. Its refractive power does not seem to have been examined.

7. *Crystalline lens.* The crystallinc weighs from 4 to $4\frac{3}{4}$ grains. It sinks rapidly in water, the specifie gravity being 10790.

No one who with eare examines the lens, can have any doubt of its lamellar and fibrous structurc.

Even in a recent cye, and before the capsule is opened, three lincs arc seen on the anterior surfacc of the lens, diverging, at cqual angles, from its vertex, towards its margin. A similar appcarance is observed on the posterior surfacc, but in a less evident degrec; the threc lines corrcsponding to the interstices of those on the anterior side. If, either within or

out of the capsule, the lens is macerated in water, these three lines open up, so that the lens separates into segments, the apices of which are turned towards the vertices or poles of the lens, and their bases towards its margin. Each of the segments consists of a succession of about two thousand lamellæ, laid one upon another like the coats of an onion, and reflected from the one surface of the lens to the other. The lamellæ are generally presumed to be concentric or parallel to one another; but Pouillet[16] represents them as unequal in curvature and thickness, and sees in this a contrivance for accommodating the eye to different distances. I believe his notion to be incorrect, for on removing the exterior lamellæ, the kernel seems to me to retain the original lenticular form. Externally the laminae adhere loosely to one another; internally much more closely; so that the density of the lens increases from the surface to the centre.

The lamellæ are composed of fibres, which become more distinctly visible by immersing the lens in alcohol, and under the microscope, present an appearance which may be compared to that of fine spun glass. The thickness of the fibres has been estimated at $\frac{1}{6000}$th part of an inch, but they become gradually more and more slender as they approach the poles of the lens. Running parallel, they are reflected from the one surface of the lens to the other, like the lamellæ which they compose. Some have observed that those fibres which present the greatest length on the one surface run the shortest course on the other. The fibres are flat; and according to Werneck,[17] they are prismatic. In all animals, they are united laterally by a series of teeth, like those of rack-work, the projecting teeth of one fibre entering into the hollows between the teeth of the adjacent one. This structure of the fibres, discovered by Sir David Brewster[18] in the lens of the cod, is much less distinctly developed in the lenses of birds and mammalia than in those of fishes. It is not improbable that the fibrous structure may depend entirely on the mode in which the lens is secreted by its capsule, and have no connexion with the function of the part.

The crystalline is composed of a much larger quantity of albumen than the other humours of the eye, so much so, as

to be entirely coagulable by the heat of boiling water. The fibres are surrounded by an albuminous fluid, containing a granular matter. The fibres are not soluble in water, but their chemical nature is not exactly known. According to Berzelius, the composition of the crystalline is as follows:—

A particular coagulable albuminous matter, .	35.9
Extract soluble in alcohol, with salts, .	2.4
Extract soluble in water, with traces of salts, .	1.3
Membrane, ...	2.4
Water, ...	58.0
	100.0

The crystalline is considerably denser, and therefore more refractive, towards the centre than on the surface; a construction, which, by shortening the focus of the rays near its axis, proves, as we shall afterwards show, of great advantage.

Chossat points out various causes, which are apt to affect the transparency of the lens, and must therefore be guarded against in experimenting on its refractive power; namely, pressure, lowering the temperature to congelation, desiccation, and absorption of ambient fluids. Operating promptly, so as to avoid desiccation, which increases the refractive power, we always arrive, in man, the ox, &c. at a central nucleus of uniform refraction. Chossat could not determine whether the refractive power increased according to any determined law. He does not state whether the following numbers refer to different layers of the lens or not, but it may be presumed that they express the increasing refractive power from the surface to the central nucleus:—

Man.	Bear.	Hog.	Elephant.	Ox.	Turkey.	Carp.
1.338	1.383	1.386	1.369	1.375	1.383	1.374
1.395	1.396	1.395	1.387	1.403	1.387	1.387
1.420	1.416	1.399	1.405	1.416	1.392	1.415
	1.436	1.424	1.415	1.432	1.396	1.436
	1.442		1.424	1.438	1.399	1.442
	1.450		1.430	1.440	1.403	1.450
	1.463		1.432			There remains a central nucleus, too hard to experiment on.
			1.436			
			1.450			

The convexity, consistence, and colour, as well as the size of the lens, vary at different periods of life. Its surfaces become gradually flatter, and its substance increases in toughness and firmness as life advances; and, although in youth, it is perfectly free from colour, in old age it assumes a yellowish or amber hue.

8. *Vitreous humour.* The vitreous body weighs about 104 grains, and consists of a transparent fluid contained in a cellular tissue formed by a membrane, called the *hyaloid membrane*, which is extremely thin and transparent, especially in the interior part of the vitreous mass. The fluid, separated from the membrane by which it is supported, differs according to Chenevix,[19] neither in specific gravity, nor in chemical composition, from the aqueous humour. Berzelius' analysis is

Common salt, with a little extractiform matter,	1.42
Substance soluble in water, . . .	0.02
Albumen, ...	0.16
Water, ...	98.40
	100.00

The refractive power of the vitreous body, according to Chossat, is as follows:—

Man.	Bear.	Hog.	Elephant.	Ox.	Turkey.	Carp.
1.339	1.349	1.339	1.340	1.338	1.338	1.349

Chossat did not separate the vitreous fluid from its supporting membrane. In his experiments, the deformation of the vitreous body, appears to have produced a considerable loss of transparency.

Sir David Brewster states the following to be the refractive powers of the humours of the eye, the ray of light being incident upon them from air, and water estimated at 1.3358:—

Aqueous humour.	Crystalline. Surface.	Middle.	Centre.	Mean.	Vitreous humour.
1.3366	1.3767	1.3786	1.3990	1.3839	1.3394

As the rays refracted by the aqueous humour pass into the crystalline, and those from the crystalline into the vitreous

humour, the relative indices of refraction of these humours will be different from the above.

When two media are in contact, they meet in the same surface, which may be called the *separating surface*. Thus the outer surface of the cornea is the separating surface between the air and the cornea; and the same holds with regard to the surface of contact of the cornea and aqueous humour; the aqueous humour and lens; the lens and vitreous humour. It is at the separating surface that the change in the direction of the ray is counted to take place, *i. e.* not within the one medium, nor within the other.

If a ray of light passes from air into the aqueous humour, the index of refraction is 1.336; if from air into the surface of the crystalline, the index is 1.3767. But if the ray passes from the aqueous humour into the crystalline, as the index of the aqueous humour is to the index of the surface of the crystalline, so is 1 to the required or relative index:—

$$1.336 : 1.3767 :: 1 : \frac{1.3767 \times 1}{1.336}$$

This amounts to dividing the index of the surface of the lens by the index of the aqueous humour, or

$$\frac{1.3767}{1.336} = 1.0304$$

The relative index, then, of the separating surface of these two media is 1.0304. In other words, the sine of the angle of refraction is to the sine of the angle of incidence, as 1 to 1.0304.

On similar principles, if we suppose an immediate passage of the ray from the aqueous humour into a body having the mean refractive power of the lens, we shall find the index to be 1.0358.

In passing from the crystalline into the vitreous humour, the refraction will be calculated in the same manner. Sir David Brewster[20] supposes the light to pass from the vitreous into the crystalline; *i. e.* from the rarer into the denser medium, which simplifies the statement, and does not alter its correctness. The meaning universally is, that if we suppose the sine in the dense medium to be 1, then the sine in the

adjacent rare medium will be the numbers set down in the tables, whether the light passes out or in. With the exception of the last, however, all the numbers in Brewster are slightly erroneous. The following are correct:—

From aqueous	humour	into	outer coat of	crystalline,	1.0304
"	"	"	"	crystalline (mean index),	1.0358
"	vitreous humour	into	crystalline	(outer coat),	1.0278
"	"	"	"	" (mean index),	1.0332

§ 51. *Powers of the lenses of the eye.*

The focal length of the eye is equal to the distance from the vertex of the cornea to that of the retina, and measures $\frac{18}{20}$ths of an inch. The focal length of a lens, or of a series of lenses placed together on the same axis, depends on the radii of the curvatures and the refractive indices of the media. We have now to examine how far these two elements contribute in each of the media of the eye, to produce the convergence of the rays of light to foci on the retina.

1. *Cornea.* Were the eye formed of one medium only, of the same refractive power as the substance of the cornea, the focus of parallel rays, falling on its convex surface, would be (§ 43) at the distance of four times its radius of curvature, or 1 inch and three-tenths, behind its anterior surface.

Rays falling on the convex surface of a bent medium, such as the cornea, would be refracted towards the perpendicular at the first surface, and from the perpendicular at the second, so that they would diverge and could not come to any actual focus.

The thinness of the cornea causes it to produce very little effect on the focal distance of the whole media; it is, therefore, generally, although improperly, disregarded in estimating the dioptric powers of the eye, and the rays of light are considered as if they fell directly on the aqueous humour.

Taking the thickness of the cornea at $\frac{1}{30}$th, the depth of the anterior chamber at $\frac{1}{10}$th, and that of the posterior at ,th, which three quantities are equal to about $\frac{23}{150}$ths of an inch, and supposing the optical centre of the lens to be $\frac{1}{10}$th of an

inch behind its anterior surface, the optical centre of the lens will be $\frac{38}{150}$ths, which is nearly $\frac{1}{4}$ of an inch, behind the anterior surface of the cornea. If we deduct this from $1\frac{3}{10}$ths, the focal length of the anterior surface of the cornea, the remainder will be $1\frac{1}{20}$ of an inch, being the distance behind the centre of the lens towards which the rays are converged by the anterior surface of the cornea.

2. *Aqueous humour.* If the rays, which have been converged at the convex surface of the cornea, passed, on quitting its concave surface and entering the anterior chamber, into a medium of the same refractive density as air, they would not only lose the degree of convergence which they had acquired, but would become divergent. Although the aqueous humour is rather less refractive than the cornea, it is so much more refractive than air, that only a small share of the convergent effect of the first surface of the cornea is lost in the aqueous humour. The aqueous humour differs from a bent medium, such as the cornea, in this respect, that its surfaces are not parallel; and from a common meniscus, in this respect, that the radii of its two surfaces are equal. By itself, then, the aqueous humour would act upon the rays of light as a convergent lens whose focus was $1\frac{1}{10}$ inch behind its anterior surface.

3. *Crystalline.* The rays, on quitting the aqueous humour, meet the capsule of the lens, a substance which is probably of considerable refractive power, but so exceedingly thin, that it produces very little effect on their direction. They now pass into the substance of the lens, which at its surface is scarcely denser than the aqueous humour. Layer by layer, however, its density increases to its centre, behind which it gradually diminishes in refractive power, till its posterior lamellæ are scarcely more refractive than the vitreous humour, from which the lens is separated by a still thinner capsule than that which divides it from the aqueous humour. It is plain, that in traversing a medium of variable density, such as the lens, the rays will undergo no sudden bending, and will not follow a rectilineal course, but will move in a gradual curve, both as they advance into the densest part of the lens, and as they retire towards the vitreous humour.

Following the rules already given (§ 43), the principal focal length of the lens, with air as the ambient medium, and taking its mean refractive index, 1.383, as a measure of its mean refractive power, would be $\frac{318}{1000}$ths, which is nearly $\frac{1}{3}$ of an inch. Monro[21] says the focus of the lens for parallel rays, as determined experimentally, is at the distance of $\frac{3}{8}$ths, which is $\frac{376}{1000}$ths of an inch, from its centre. He remarks that a glass lens of the same size and shape would collect parallel rays at the distance of $\frac{1}{4}$ of an inch, and one of water at $\frac{1}{2}$ an inch, so that the crystalline has a power half way between that of glass and water.

Young[22] considered the refractive power of the centre of the human crystalline, during life, to be to that of water nearly as 18 to 17; the water imbibed after death, reducing it to the ratio of 21 to 20; but, on account of the unequal density of the lens, he estimated its effect in the eye as equivalent to a refraction of 14 to 13 for its whole substance. From this statement it would appear, that he regarded the power of the crystalline as greater than that of a lens of the same dimensions, and having the refractive power even of the nucleus. The grounds for such an opinion may be thus explained :—

The principal focus of a sphere of glass, whose index of refraction is 1.5, would be at the distance, *f*, fig. 40, of $1\frac{1}{2}$ radius from its centre. The principal focus of a sphere formed of a substance whose index of refraction is 1.75, would be at the distance of $1\frac{1}{3}$ of its radius from the centre. A sphere of zircon, with a refractive index of 2, would have its principal focus exactly at the extremity of the diameter, and consequently in the surface of the sphere. If within a sphere of glass, a sphere of zircon was enclosed, of half the diameter of the sphere of glass, and so placed that the two spheres had the same centre, it is evident that parallel rays, falling on the sphere of glass, would acquire a convergence towards a focus at the distance of three radii from the anterior surface of the sphere, but that parallel rays falling on the sphere of zircon would be converged to the point where the diameter meets the posterior surface. Rays, consequently, which had already been converged by passing through one side of the shell of

glass, on being refracted by the zircon, would come to a focus considerably within the sphere.

Now, as rays, falling upon a convex lens parallel to its axis, are refracted in precisely the same manner as those which fall upon a sphere, the focal length of a compound lens, like the crystalline, must be shorter than that of a lens having the same curvatures and the *mean* refractive index of the crystalline, and even than that of a lens having the same curvatures with the containing lens and the *maximum* index of refraction corresponding to that of the contained lens.[23]

4. *Vitreous humour.* The vitreous humour, were it insulated from the other lenses of the eye, would act on parallel rays as a meniscus with its concave surface turned forward. But as it receives the rays from a medium denser than itself, it aids feebly their previous convergency.

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1 Encyclopædia Metropolitana, Article *Light*, § 359.

2 Gerson, De Forma Corneæ, 17; Gottingæ 1810.

3 Annales de Chimie et de Physique, x. 337; Paris 1819.

4 Encyclopædia Metropolitana, Article *Light*, § 350.

5 Oculus, 8; Œniponti 1619.

6 Histoire de l'Académie Royale des Sciences, 1741, p. 70.

7 Dioptrice, prop. lx. p. 22; Augustæ Vindelicorum 1611.

8 Handbuch der theoretischen und practischen Augenheilkunde, I. 226; fig. 2; Wien 1830.

9 Philosophical Transactions for 1822, pl. 6. fig. 3.

10 Animal and Vegetable Physiology considered with reference to Natural Theology, ii. 471. fig. 415; London 1834.

11 Op. Cit. 64.

12 Philosophical Transactions for 1802, 369.

13 Annales de Chimie et de Physique, viii. 217; Paris 1818.

14 Edinburgh Philosophical Journal, i. 42; Edinburgh 1819.

15 Poggendorf's Annalen der Physik und Chemie, xxxviii. 313; Leipzig 1836.

16 Elémens de Physique Expérimentale et Meteorologie, ii. 331. pl. 6. fig. 229; Paris 1829.

17 Zeitschrift für die Ophthalmologie, v. 404; Heidelberg 1837.

18 London and Edinburgh Philosophical Magazine for March 1836.

19 Philosophical Transactions for 1803, 198.

20 Treatise on Optics, 289; London 1831.

[21] Three Treatises. On the Brain, the Eye, and the Ear, 89; Edinburgh 1797.

[22] Philosophical Transactions for 1801, 42.

[23] Young's Lectures on Natural Philosophy, ii. 82; London 1807.

CHAPTER VIII.

THE EYE CONSIDERED AS A DIOPTRIC INSTRUMENT.

§ 52. *Experiments showing inverted images on the retina.*

The manner in which images of external objects are formed on the retina may be illustrated by means of the instrument called an *artificial eye*, in which the cornea and humours are imitated in glass, the back of the piece which represents the vitreous humour being rough-ground, so as to be semi-opaque.

It is better, however, to take a human eye, the eye of a white rabbit, or, should neither of these be at hand, the eye of a sheep; clean it of the muscular and cellular substance which adheres to it; and, if it is a sheep's eye, pare away part of the thickness of the sclerotica, round the optic nerve. If the eye is now held with the cornea towards a lighted candle, an inverted image of the candle will be seen through the sclerotica, choroid, and retina, at the back of the eye; and it will be observed that the situation of the image varies according to the place of the candle, and the size according to its distance. If the candle is elevated, the image will sink; if the candle is depressed, the image will rise. If the candle is moved to the right, the image will shift to the left, and *vice versa.* The size of the image will increase as the candle approaches to the eye, and diminish as it recedes from it. In the eye of a white rabbit, the sclerotica is thin and the choroid destitute of pigment, so that if we hold up such an eye towards the street, or insert it into a hole in one of the closed

window-boards, distinct inverted images of the houses and passengers are seen through the sclerotica.

We know (§ 8, 9) that images, similar to those seen in these experiments, would be formed, although the eye was entirely destitute of refractive media, and consisted merely of a hollow sphere, with a pin-hole in front to admit the light, and a screen, in the situation of the retina, to receive the images. A much greater quantity of light is admitted, and a wider field of vision obtained, by enlarging the aperture of transmission to the size of the pupil; while by means of the refractive media of the eye, the images are rendered more vivid and distinct than if the eye had been a simple camera obscura.

From every point of a luminous object, such as the lighted candle in the above experiments, there flows a cone of light, the base of which falls upon the eye, and by the cornea and humours the diverging rays of each cone are collected again to a point upon the retina. We are naturally led to inquire into the share which the cornea and the several humours take in the production of this effect.

§ 53. *Refractions within the eye.*

The dioptric effects of the lenses of the eye are chiefly two; viz. that of the cornea and aqueous humour in *first* rendering the rays of light convergent, and that of the crystalline in *finally* bringing those rays to focal points on the retina.

Let R, R′, fig. 56, be parallel rays, falling on the eye at

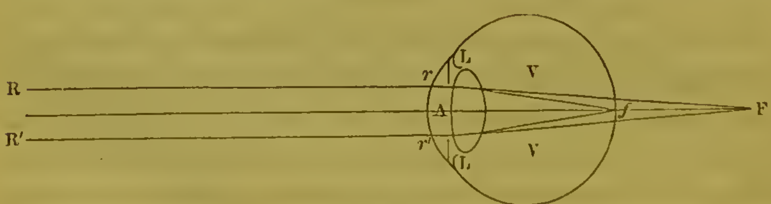

Fig. 56.

r, r'. The cornea and the aqueous humour, A, being about the same density as water, and presenting a convex surface to the rays, R r, R′ r', they would be made to converge towards

a point, F, at the distance of four times the radius of the convexity of the cornea, if the whole cavity of the eye were filled with aqueous humour. But the point F being beyond the eye, makes it necessary that some other body, of greater density than the aqueous humour, should be interposed, in the form of a convex lens, sufficiently refractive to gather the rays to a point within the eye. This is effected by the crystalline, L L.

If the rays of light, on quitting the concave surface of the aqueous humour, met the convex surface of a medium of like density with the crystalline, and filling the whole posterior part of the eye, the rays would, by the anterior surface of such a medium, be converged to a focus a little beyond the eye. But the posterior convex surface of the crystalline necessarily producing a new convergence of the rays, they are brought exactly to a focal point, *f*, on the retina. Had the density of the vitreous humour, V V, been greater than it is, the focus would have been behind the retina; had it been less, the focus would have been before the retina.

In order to illustrate more fully how the several lenses of the eye conduce to form an image of external bodies on the retina, let A *r*, A *s*, A *t*, fig. 57, be rays flowing from the point

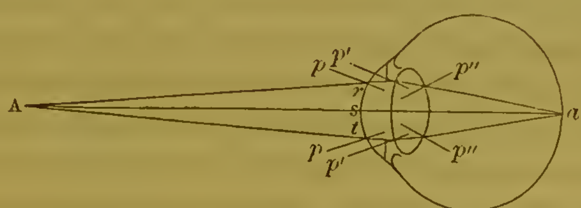

Fig. 57.

A, of an object, placed at a convenient distance before the eye, and towards which its axis is directed. Of these rays, we shall suppose the middle one, A *s*, to be in the axis of vision, and to fall perpendicularly on all the humours of the eye, although, as we shall afterwards explain, this cannot really be the case with any ray of light, on account of the cornea and humours not being placed on one axis. Suppose, then, this ray to move straight on to *a*, at the centre of the retina, without suffering any refraction. The other rays of the pen-

cil, as A r, A t, by falling obliquely on a medium which is denser than the air, such as the cornea or the aqueous humour, will be refracted towards the perpendicular. Let therefore the lines p, p, be drawn perpendicularly to the cornea at the points of incidence, r, t. It is evident that the rays, by being refracted towards these perpendiculars, will, if parallel, as R R′, in fig. 56, become convergent, and if divergent, as A r, A t, in fig. 57, they will either have their divergence lessened, or even be made to converge. By this *first* refraction, which the rays of light suffer in falling upon the eye, they are brought nearer to one another, so that more of them may pass through the pupil, and not be lost upon the iris.

A *second* refraction which the rays suffer, is in passing out of the aqueous humour into the crystalline; by which refraction, they are made to approach still more to one another than before; for the crystalline being denser than the aqueous humour, the rays must here also be refracted towards the perpendiculars, p', p'. These perpendiculars, on account of the convex surface of the crystalline, approach one another, and therefore the rays, which by refraction are brought towards these perpendiculars, must also become more convergent.

There is yet a *third* refraction, as the rays pass out of the crystalline into the vitreous humour; for the crystalline being denser than the vitreous humour, the light, in quitting the former to enter the latter, will be refracted from the perpendiculars p'', p''. But as the surface of the vitreous humour is concave, answering to the posterior convex surface of the crystalline, these perpendiculars must recede from one another, and consequently the rays by being bent from these perpendiculars, must be made yet more to converge, and approach each other.

By these several refractions, then, the rays of light proceeding from the point A, are made to converge, and meet again on the retina in a focal point, a.

It is plain, that the greatest degree of refraction, which the rays of light passing through the eye undergo, is the first, viz. that which occurs on their entering the cornea; because the difference between the air and the cornea, as media, is

much greater than that between the aqueous humour and the crystalline, the relative index of air and the cornea being 1.3296, while that of the aqueous humour and the surface of the crystalline is only 1.0304. When the rays which fall upon the eye are parallel, as in fig. 56, and the pencils which are permitted to pass into the lens are slender, as is the case when the light is tolerably bright and the pupil contracted, the refractions produced by the lens and vitreous humours have little influence on the rays, farther than permitting them to continue in the direction already impressed on them. Such rays, on quitting the cornea, move to the retina, in lines which it would be difficult to distinguish from straight lines. Distant objects, therefore, being seen by means of parallel rays, appear with tolerable distinctness to a person who has had the crystalline extracted.

It is a common remark, that the cornea, aqueous humour, and crystalline, act together upon the rays of light exactly like a double-convex lens, and that consequently inverted images of external bodies are formed upon the retina, in precisely the same manner as if the retina were a piece of paper in the focus of a single lens, of the same power as those parts united. This statement might lead the student to attribute too much to the power of the lens, which is comparatively slight, the chief refraction being at the surface of the cornea. It is there that the rays receive the convergence, which is little more than continued by the crystalline, whereas in a double-convex lens, (fig. 26), as much of the convergence occurs when the rays quit its posterior surface as when they traverse its anterior surface.

Besides bringing the rays to focal points on the retina, the crystalline aids in diminishing the image; but so little, that its extraction on account of cataract, does not make objects appear larger.

The principal use of the vitreous humour seems to be that of giving a ready passage to the rays of light, as they are converging to foci on the retina, and of keeping at the same time the surface of the retina uniformly supported. It is generally presumed, that the vitreous humour would admit a

change of figure in the eye, or in the lens, or even a change of place in the latter, supposing there were powers in the living organ, adequate to the purpose.

The pencils of rays proceeding from any object, as they arrive at the surface of the cornea, form cones, the points of which are at the object, and the bases at the cornea. Those which impinge on the sclerotica are reflected, and have no concern in the production of vision. Although all the rays which fall on the cornea are not transmitted by it, but a considerable portion of them reflected, still a sufficient number even of those which fall nearest to the margin of the cornea, and at right angles to its axis, enter the eye, and reach the retina. The rays which pass into the cornea undergo a certain amount of refraction, by which they are brought nearer to the line of its axis, and if produced in the direction of their first refraction, would converge, as has already been explained, into a focal point beyond the back of the eye. From the cornea, the rays pass into the aqueous humour, and if continued in the same medium, would still be brought to a focus only beyond the back of the eye. The rays collected by the cornea are converged towards the pupil. Those which come in an unfavourable direction are either reflected by the iris, or absorbed by the pigment on its posterior surface. The rays admitted by the pupil meet with the crystalline, which still farther converges them, so that after passing through the less refractive medium of the vitreous humour, they are brought to foci on the concave surface of the retina.

The rays could not impart a correct perception of the object which emits or reflects them, unless they fell on the retina precisely in the order in which they are detached from the object. To produce this effect, all the rays, which proceed from any one point A, fig. 58, of the object, must be collected

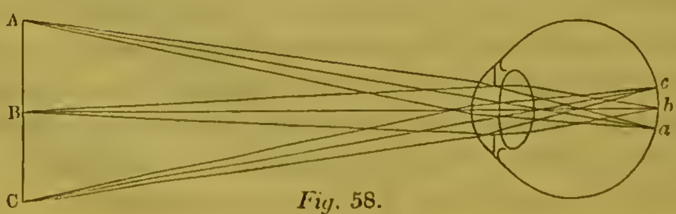

Fig. 58.

on one point, *a*, of the retina, and all the points of union, *a*, *b*, *c*, thus formed, must be disposed upon that membrane as in the body, A B C, of which they form an image.

The cone of rays which proceeds from every point of the object to the cornea, forms another cone within the eye, the apex of which falls on the retina. The axis of each of these cones, such as A *a*, is almost in a straight line. That which is perpendicular to the middle of the crystalline is presumed to fall on the vertex of the retina; that which comes from the upper extremity of the object strikes the retina inferiorly; that from the lower end strikes it superiorly; and so on with respect to the others; and thus an inverted image is formed on the retina.

That the axis, A *a*, C *c*, of each of the oblique cones is not absolutely in a straight line, arises from the curvature of the anterior surface of the crystalline being the same as that of the cornea. The surfaces of the cornea and crystalline, therefore, not being concentric, (§ 51) they must incline towards each other, and consequently even the rays which traverse the cornea perpendicularly, must fall obliquely on the anterior surface of the crystalline, and there suffer refraction. For a reason immediately to be explained, the ray which coincides with the axis of the cornea is also refracted.

§ 54. *Optic or visual axis. Axes of cornea and crystalline not coincident.*

On the presumption that the eyeball and all its parts were symmetrical, it was natural to conclude that the centres of the spheres to which the cornea, the ball of the eye, and the two surfaces of the crystalline were supposed to belong, were all placed in the same right line. To this line the name of *optic axis* was given, and it was supposed that being produced both ways, it passed through the centres of the cornea and retina, considered as surfaces. All this, however, is incorrect. The centre, neither of the cornea, nor of the crystalline, is in the axis of the eyeball, and some have been inclined

to consider even the anterior pole of the crystalline as not directly opposite to the posterior. That the crystalline is not situated in the middle line of the eye, but more inwardly or towards the nose, is seen by dividing the eye into a nasal and a temporal half, when the middle of the crystalline will be found in the inner or nasal portion. The centres of the pupil and iris do not correspond; the former being nearer the nose than the latter. The centre of the pupil appears to be placed in the line of the axis of the crystalline, while that of the iris is in the line of the axis of the cornea or of the globe of the eye.

A consequence of the non-coincidence of the cornea and crystalline is, that, contrary to what appears to have been generally supposed till Wells pointed out the fact, no ray of light can pass unbent to the retina from the atmosphere, or any other medium differing in refractive power from the aqueous humour. The ray which coincides with the axis of the cornea will fall to one side of the axis of the crystalline, and, therefore, entering it obliquely, will be refracted. The phrase *optic* or *visual axis* is still retained by Wells;[1] but a more accurate signification is annexed to it. When a small object is so placed with respect to either eye, as to be seen more distinctly than in any other situation, Wells says it is in the optic axis, or the axis of that eye; and if another small body be interposed between the former and the eye, so as to conceal the first body, and a line joining the two be produced till it falls on the cornea, he calls this line the optic axis, or the axis of the eye, without determining the precise point of the cornea it falls upon, or what part of the retina receives the image of an object which is placed in it. This line, however, cannot fall at any great distance from the vertex either of the cornea or of the retina.

§ 55. *Focal centre of the eye. Visual angle. Size of the image. Apparent magnitude of the object.*

There are few subjects upon which optical authors have allowed themselves to speak so loosely, as what they have

called the *focal centre* of the eye. They have defined this term to signify a point in the axis of the eye, at which the image on the retina and the object subtend equal angles, whereas there is in reality no fixed point which answers this description. While some have placed this supposed point of equal decussation for the rays bounding the extremities of the object and the image, in the vertex of the cornea, others have placed it in the middle of the pupil, others in the centre of the crystalline, and others in the centre of the eye.

Were the eyeball filled entirely with aqueous humour, supported anteriorly by a cornea whose surfaces were spherical, its focal centre would be the centre of curvature of the cornea. The optical centre (§ 42) of the crystalline, considered by itself, would be its focal centre. But the rays, which proceed through the cornea and aqueous humour, and which would decussate at the centre of curvature of the cornea, meet the crystalline, and are refracted by it out of their former course, and made to converge, so that the angle subtended by the image is less than that subtended by the object.

The eye, considered as a compound lens, will have its focal centre somewhere between the focal centres of the cornea and crystalline, and consequently not far from the posterior surface of the latter.

The rays, Q C, S C, represented in fig. 59, as decussat-

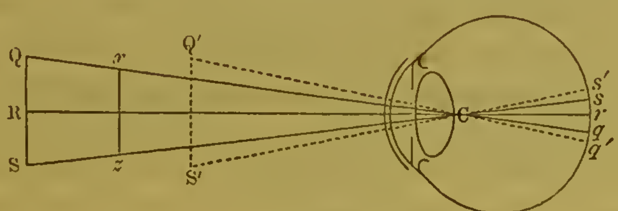

Fig. 59.

ing at the focal centre of the eye, are those which are accounted the axes of the pencils, which, proceeding from the extremities of the object, Q S, pass through the pupil. The angle, Q C S, which they form at the focal centre, is called the *visual angle.* Crossing each other, and suffering a slight convergence, these rays are prolonged to the retina, and thus form a second angle, *s* C *q*, subtended by the image, *s q*, and

rather less than the visual angle, with which, however, it increases and diminishes, according to the magnitude and distance of the object. The size of the image on the retina determines the *apparent magnitude* of the object, and the angle which the image subtends is in a constant but unknown ratio to the visual angle. It might at first sight seem easy, by following the law of the sines, to trace, by geometrical construction or by calculation, the path of any ray through the refractive media of the eye, and to determine the point where the ray emanating from one extremity of an object would intersect that which comes from the other extremity; but the minuteness of the parts, the departure of their curvatures from the curvature of a sphere, and the unequal density of the crystalline, render the problem so difficult that it has not yet been solved. No sensible error, however, will result from supposing the focal centre of the eye, C, to be $\frac{6}{10}$ths of an inch in front of the vertex of the retina, r; nor from neglecting the small decrement which the angle subtended by the image suffers from the convergent power of the lens. We may safely substitute, therefore, the visual angle, under which any object is seen, as a measurement of its apparent magnitude.

In fig. 59, the object Q R S subtends the angle Q C S, and its image the angle s C q. The object $x\,z$, which is smaller than Q S, but nearer the eye, is seen under the same visual angle, and forming an image of the same size, $s\,q$, will therefore have the same apparent magnitude. The object Q S has the same linear magnitude as Q S, but being nearer the eye, it subtends a larger visual angle Q′ C S′, forms a larger image, $s'\,q$, on the retina, and will therefore have a greater apparent magnitude. When any object, as Q S or Q′ S′, is viewed at different distances, its image and apparent magnitude will increase, very nearly in the same proportion as the distance between the focal centre and the object decreases; and, on the contrary, will decrease in the same proportion as that distance increases.

$$\text{R C} : \text{C}\,r :: \text{Q S} : s\,q$$

Therefore, $s\,q = \frac{\text{C}\,r \times \text{Q S}}{\text{R C}}$, but since C r, the distance of the

image from the focal centre, has been assumed .6, we have

$$s\,q = \frac{.6 \times \text{Q S}}{\text{R C}}.$$

For example, if a man, 6 feet high, is seen at the distance of 20 feet, his image on the retina, by this formula, will be $\frac{.6 \times 6}{20} = \frac{18}{100}$ of an inch. The linear magnitude of the image of a mountain, 5000 feet high, seen at the distance of 5 miles, will be $\frac{.6 \times 5000}{26400} = \frac{5}{44}$ or nearly $\frac{1}{9}$ of an inch. The diameter of the moon's image on the retina, taking her distance to be 240,000 miles, and her diameter 2144 miles, will be $\frac{.6 \times 2144}{240000}$ or nearly $\frac{1}{186}$ of an inch.

The area, of course, of the image is to that of the object, as the square of the distance from the focal centre to the retina, to the square of the distance of the object from the focal centre.

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[1] Essay upon Single Vision with Two Eyes, 19. London 1818.

CHAPTER IX.

OPTICAL ABERRATIONS. SPHERICAL ABERRATION. CORRECTION OF SPHERICAL ABERRATION IN THE EYE.

§ 56. *Three optical aberrations.*

THAT the images formed upon the retina, and the concomitant impressions upon which visual sensations depend, may be perfect, it is necessary that all the rays of light which pass through the lenses of the eye and reach the retina, shall accurately converge and meet in their respective focal points upon that membrane. Now, there are certain optical *aberra-*

tions, as they are termed, which if not obviated in the eye, would render vision indistinct or confused. We proceed to examine these aberrations, and the modes in which they are lessened or prevented in the structure of this organ.

The aberrations in question are connected with the passage of light through lenses, and are three in number, viz. *spherical aberration*, *chromatic aberration*, and *distantial aberration*. The *first* depends on the spherical form of lenses; the *second* on the separation into the prismatic colours, which white light undergoes in passing through refractive bodies; and the *third* on the various distances at which objects are presented to a dioptric instrument.

§ 57. *Spherical aberration explained.*

Parallel rays entering any plano-convex or double-convex lens at an equal distance from its axis are concentrated to the same focal point; for the angles of incidence of such rays are equal to one another, as are also their angles of refraction. In the same manner, in a cone of light, of which the axis is coincident with the axis of the lens, all the rays of the cone which strike the lens in a circle, and consequently at the same distance from the axis of the lens, will be concentrated to one focal point.

We have already seen (§ 22) that to bring parallel rays to a focus, their refraction must increase in proportion as they are farther from the axis of the convex lens to which they are presented. It is a fact, however, which was observed soon after the discovery of the ratio of the sines or true law of refraction (§ 27), that the rays of any considerable pencil of light could not be brought to a focal point, by any lens, which was throughout of uniform density, formed by spherical surfaces, and having everywhere the same degree of curvature. On the contrary, it was found that the rays near the axis of such a lens were refracted to a more remote focus, while those which were incident farther from the axis were refracted to a nearer focus; in other words, the exterior rays of the pencil were too much, and the interior too little bent, to meet in one point.

Let L L, fig. 60, be a double-convex lens of glass, whose

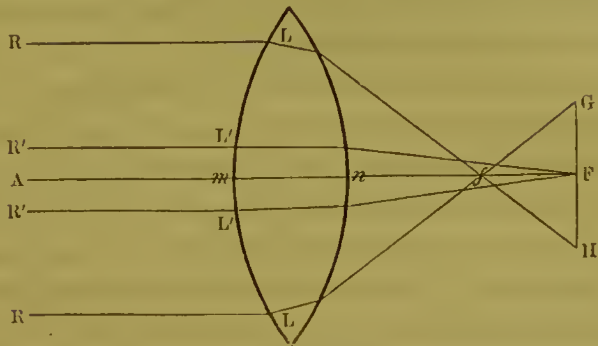

Fig. 60.

surfaces are segments of spheres, and let its surface L *m* L be turned towards parallel rays. Let R′ L′, R′ L′ be parallel rays very near the axis A F of the lens, and let F be their focus after refraction. Let R L, R L be parallel rays incident near the margin of the lens, and it will be found, by construction, that the corresponding refracted rays L *f*, L *f* will meet at a point *f*, much nearer the lens than F. In like manner intermediate rays between R L and R′ L′ will have their foci intermediate between *f* and F. Continue the rays L *f*, L *f*, till at G and H they meet a plane passing through F. The distance *f* F is called *longitudinal* spherical aberration, and G H *lateral* spherical aberration.

In an equi-convex lens of glass, the longitudinal spherical aberration, *f* F, is stated by Sir David Brewster[1] to equal 1.067 of its thickness, *m n*. In the figure, *f* F will be observed less than this, but had the rays R L, R L, fallen on the margin of the lens, and the rays R′ L′, R′ L′, nearer the axis, the distance of the points *f*, F, would have been equal to 1.067 of *m n*.

If such a lens is exposed to the sun, or to a lighted candle, the central part of it L′ *m* L′, whose focus is at F, will form a bright image of the sun at F; but as the rays of the sun which traverse the lens near its circumference, have their foci at points between *f* and F, the rays will, after arriving at these points, pass on to the plane G H, and occupy a circle whose diameter is G H. Hence, the image of the sun in the focus F will be a bright disc, surrounded and rendered indistinct by a broad halo of light, growing fainter and fainter from F to G

and H. In like manner, every object seen through such a lens, and every image formed by it, will be rendered confused and indistinct by spherical aberration.

Suppose such a lens as L L occupied the place of the crystalline, and that the retina were situated either at F, or at *f*, or at any intermediate point, it is plain that with the focus of one set of rays, it would receive others not brought to a focus, the consequence of which would be that the image would be diluted from want of due concentration of the rays, and would be surrounded by a halo.

If the student takes a ring-shaped screen of black paper, and covers with it the circumferential portion of one or other of the surfaces of a lens, the halo G H, and the indistinctness of the image, will be lessened. If he covers all the lens, excepting a small part in the centre, the image will become perfectly distinct, though less bright than before, and the focus will be at F. The image will also be defined at *f*, if the light be allowed to pass through the circumference of the lens only, and not through its centre, for then the halo formed by the central rays around the focus of the marginal rays will be avoided.

§ 58. *Spherical aberration modified by certain relations between the spherical surfaces of lenses.*

The aberration from sphericity may be diminished to a very great extent, by altering the relation of the curves of the two spherical surfaces of lenses. For instance, if the convex surface of a meniscus is turned towards converging rays, they are all brought to one focus, provided the distance of the point of convergence from the centre of the first surface is to the radius of the first surface as the index of refraction is to unity. The refraction produced by the first surface, in this case, causes the converging rays to fall perpendicularly on the second surface, and hence upon its centre of curvature, without any aberration.[2]

The double-convex lens which has the least spherical aberration is one, the radii of whose surfaces are as 1 to 6. When

the face whose radius is 1 is turned towards parallel rays, the aberration equals 1.07 of its thickness; but when the side with the radius 6 is turned towards parallel rays, the aberration is equal to 3.045 of its thickness.[3]

§ 59. *Spherical aberration obviated by elliptical and hyperbolical lenses.*

The central parts of the lens L L, fig. 60, refract the rays too little and the marginal parts too much. If the convexity could be increased towards *m* and *n*, and diminished gradually towards L L, the spherical aberration would be removed. This would be to change the lens from the spherical to some other figure, but unfortunately the spherical is the only curve which can be given to the surfaces of lenses by grinding. The ellipse and the hyperbola are curves of such a nature that their curvature diminishes from *m* to L; and it was shown by Des Cartes[4] how spherical aberration may be entirely removed by lenses whose sections are ellipses or hyperbolas.

Thus, if A L′ M L′, fig. 61, be an ellipse, whose major axis,

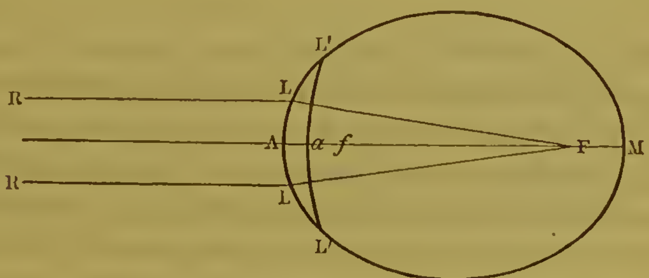

Fig. 61.

A M, is to the distance between the foci, *f*, F, as the index of refraction of the substance of the ellipsoid is to unity, parallel rays, R L, R L, incident upon the elliptical surface, L A L, will be refracted by that surface so as to meet in the focus F, if no second surface intervenes. If with F as a centre, an arc of a circle L′ *a* L′ be described, this will represent a second surface for the lens L′ L′, and as this surface meets the rays refracted by the first surface perpendicularly, it will not change the direction they have acquired.

§ 60. *Cornea and crystalline supposed to be elliptical or hyperbolical.*

It has long been the general opinion of optical authors, that spherical aberration is obviated in the human eye, at least in part, by the cornea and the crystalline being actually bounded by surfaces which are not spherical, but formed by the revolution of a conic section, such as an ellipse or a hyperbola. Here I must refer the reader to what has already (§ 49) been said on the curvatures of the lenses of the eye. If it is really the case, that the surfaces of the cornea and crystalline are formed by one or other of the curvatures now mentioned, the angles of incidence under which the oblique pencils meet those surfaces will be lessened, and the aberration which would have subsisted, had the surfaces been spherical, will be almost completely destroyed.

§ 61. *A combination of lenses obviates spherical aberration.*

With regard to glass lenses, it is perfectly ascertained that by combining different spherical lenses, spherical aberration may be wholly removed. The aberrations produced by a convex and concave lens, or by a double-convex lens and a meniscus, tend to correct each other. By a proper adjustment, therefore, of the radii of the surfaces, a compound lens may be constructed, which will entirely destroy the aberration. Such a combination forms an *aplanatic*[5] lens. Whether the combination which exists in the eye is calculated to ensure this effect, has not been ascertained.

It is possible that the student may think he has not sufficient grounds either for admitting or rejecting the hypothesis, that the curvatures of the lenses of the human eye, or their combination, produce the desired effect; but there are two other methods capable of correcting spherical aberration, which are evidently adopted by nature in the construction of the eye. The one is the use of what opticians term a *diaphragm*, and the other is the peculiar structure of the crystalline lens.

§ 62. *Use of a diaphragm. Aperture of a lens.*

A simple experiment has already shown us (§ 57), that by excluding the light from the circumferential portion of a lens, we avoid the halo which surrounds the image of the sun, or of a lighted candle, when the whole lens is employed, and form a clear and well defined image by means of the central portion employed alone. A screen for this purpose is called a *diaphragm* or *stop*, and almost all dioptric instruments are furnished with such a contrivance. The angle under which the diaphragm permits the lens to be seen from the principal focus, is called the *aperture* of the lens; and in optical instruments, intended to operate with correctness, this angle should not exceed 20° or 30°, in order that only those luminous pencils may be admitted which are but slightly inclined to the axis. It follows that both in their incidence and in their emergence, the rays of light meet the refracting surfaces almost perpendicularly. Spherical aberration is thereby prevented, and well defined images are obtained.

§ 63. *The iris a diaphragm.*

The existence of a diaphragm is one of the most striking particulars in the structure of the eye.

It is placed a little way anterior to the crystalline lens, and is immersed in the aqueous meniscus so as partially to divide it into two portions, the anterior and posterior chambers, which communicate through the pupil.

Being opaque, the iris arrests those rays of light which enter the eye very obliquely, or at too great angles with the axis of the crystalline, and which, were they allowed to traverse the lens, could not be refracted to focal points equidistant from the lens with those rays which traversed that body near its axis; but, on the contrary, would be refracted to focal points less remote from it, and consequently anterior to the retina.

The iris does the same with respect to the cornea and aqueous humour.

This diaphragm, being placed in the aqueous lens, and close in front of the crystalline, acts with greater effect than it could have done in any other situation. As has been already (§ 53) explained, every point of every visible object sends into the eye a cone of luminous rays, having its base over the whole external surface of the cornea. This cone, in being refracted by the aqueous humour, is changed into a shorter cone, which has its apex in the interior of the eye. Obliged to traverse the pupil, a small circular aperture concentric or nearly concentric with the axis of the organ, it loses all those of its rays whose primitive obliquity of incidence upon the cornea would have produced too great a degree of spherical aberration; and this favourable exclusion, from the interior situation of the iris, operates with equal success, whatever be the direction of their incidence.

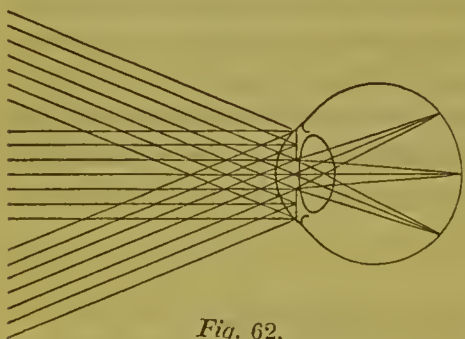

Fig. 62.

In place of this arrangement, the effect of which is illustrated by fig. 62, suppose that the iris, having still the same size of aperture, had been placed outside the eye, or on the exterior surface of the cornea, as in fig. 63, it would still have exercised its effect, but uselessly, on the cones incident near to the axis; but for the oblique cones, it would have been very defective. It would have admitted exactly the rays the most remote from the axis, and the most oblique to the surface of the cornea, the rays precisely which should be rejected and which in fact the internal diaphragm excludes; so that, to obtain the same exclusion by means of an external iris, there would have been

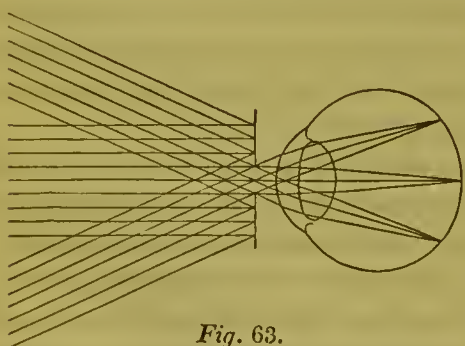

Fig. 63.

no other resource but to have made its aperture extremely small.

The situation of the diaphragm, then, in the aqueous lens, is a means of admitting a greater quantity of light with a less aberration of sphericity. This is, no doubt, the reason why it is thus placed in an organ, all the parts of which are constructed with so much perfection. Human art, coarse as it is in comparison with the works of nature, has employed the same contrivance; for such is precisely the construction of Wollaston's periscopic microscope, which consists of two plano-convex lenses, their plane surfaces turned towards each other, but partially separated by a diaphragm. This compound lens has undoubted advantages in regard to the quantity of light it transmits, and the distance from the axis to which it permits vision to be extended.[6]

§ 64. *Increasing density of the crystalline from its periphery inwards.*

We have seen (§ 50), that the crystalline consists of fibres of extreme tenuity, closely arranged in its nucleus, but surrounded by more and more fluid, and consequently connected more and more loosely as they approach its circumference and its surfaces. The effect of this arrangement is, that the circumferential portion of the lens is much less dense, and having a less specific gravity than its central portion, must of course possess a less refractive power. The refractive power, indeed, diminishes gradually from the centre in every direction to the periphery, so that the rays of light which traverse the crystalline, instead of being converged the more rapidly the farther they are from its axis, which we have seen (§ 57) to be the case in spherical convex lenses of uniform density, are probably all brought exactly to one focus on the retina.

To compute the effects of a lens, formed by two elliptical surfaces, and of varying consistence from its periphery to its centre, would be exceedingly difficult. We are certain, that had the crystalline been a lens of uniform density throughout,

it could not have united a pencil of parallel or divergent rays into one focus. This is in all probability ensured by the gradual increase of density which it presents from without inwards. The motion of the rays of light through a lens of uniform density, having the same thickness as the crystalline, but formed of spherical segments, would be in straight lines, and on account of the shortness of the focal distance of the eye, in proportion to the aperture of the pupil, the aberration of the oblique rays would be very considerable. Formed by elliptical segments, and consisting of an infinite succession of layers, increasing in density by insensible gradations, so that while its surface presents nearly the same refractive power as water, 1.3767, the refractive power of its centre is 1.3990, it will bend the rays in gradually increasing curves from its axis to its circumference, and probably brings both the direct and the oblique pencils to the same focal points.

§ 65. *Summary of the means by which spherical aberration is obviated in the eye.*

Spherical aberration is corrected, then, or supposed to be corrected, in the human eye:—

1st. By the figure of the cornea and crystalline; not being spherical, but elliptical or hyperbolical.

2d. By the intervention of a stop or diaphragm.

3d. By the increasing density of the crystalline from its periphery to its centre.

The 1st. and 2d. of these contrivances are imitable, and have often been imitated. Indeed a diaphragm is used in almost all dioptric instruments. But the 3d. seems inimitable by human ingenuity.

§ 66. *Experimental proof that spherical aberration is obviated in the eye.*

As far as can be ascertained by the optometer, the aberration arising from figure is completely corrected in the eye. If we look through four slits in a card held perpendicularly,

at a line drawn upon a piece of pasteboard, placed horizontally, which is equivalent to using an optometer with four slits, the four images of the line appear to cross each other exactly in the same point, which they could not do if the lateral rays were materially more refracted than the rays near the axis.[7]

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[1] Treatise on Optics, 54; London 1831.
[2] Ib. 56.
[3] Ib. 54.
[4] Discours de la Méthode pour bien conduire sa Raison, 187; Paris 1668.
[5] *Aplanatic,* without aberration, from α privative, and πλάνη *error.*
[6] Philosophical Transactions for 1812, 375.
[7] Young, Philosophical Transactions for 1801, 49.

CHAPTER X.

CHROMATIC ABERRATION. ACHROMATISM OF THE EYE.

§ 67. *Decomposition and dispersion of light explained.*

We have hitherto spoken of light as if it were homogeneous, and suffered an equal degree of refraction whatever might be its colour. We have now to explain what is meant by the *decomposition* and *dispersion* of light.

If a beam of the sun's light, S L, fig. 64, fall upon a plane refracting surface, A B, instead of the whole of it, as we have hitherto supposed, being bent into one direction, the beam is dispersed or spread out in the plane of incidence, so as to fill an angular portion of that plane, included between cer-

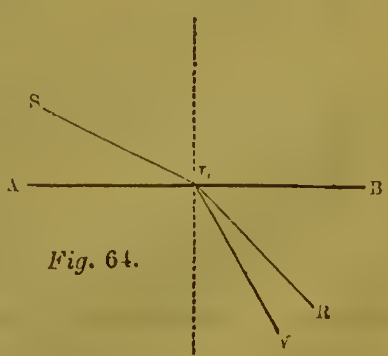


Fig. 64.

tain directions, L R and L V. This fan of light consists of differently coloured rays proceeding from the centre L; the least refracted rays, or those about L R, being red, and the most refracted rays, or those about L V, being violet. Thus it is that white light is *decomposed* and *dispersed* by refraction. By one refraction, these effects are produced in a degree which is scarcely sensible; but by two refractions, at inclined surfaces, they become conspicuous.

§ 68. *Newton's discovery of the heterogeneousness of light. Fourth law of light.*

Previously to the discoveries of Newton, light of every colour was believed to be equally refracted; and though it was a familiar experiment before his time, to produce colours, like those of the rainbow, by means of a prism, no philosopher seems to have examined the fact with sufficient attention.

In hopes of improving the telescope, by giving to its lenses a figure different from the spherical, Newton, in 1666, procured a triangular glass prism, in order, as he tells us, to try with it "the celebrated phenomena of colours." Having made a hole in one of his window-shutters, and darkened his chamber, he let in a beam of the sun's light, S L, fig. 65,

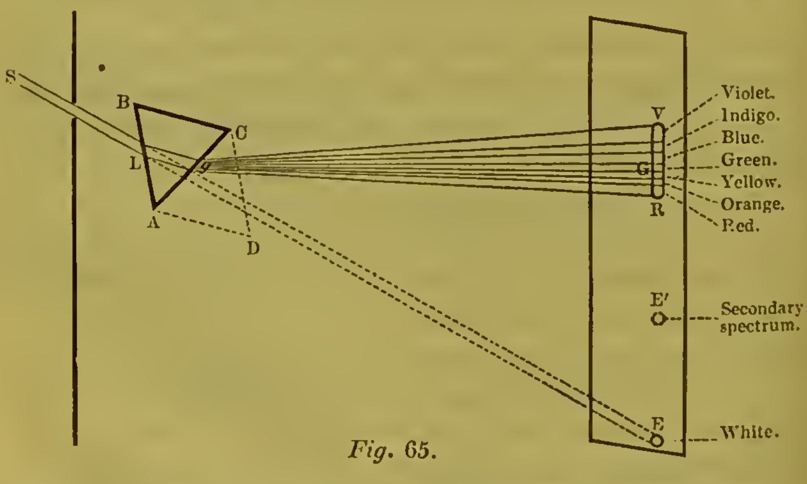


Fig. 65.

which, if not interfered with, proceeded in a straight line to E, where it formed on the wall, or on a screen placed to re-

ceive it, a white round spot. But if he so placed the prism, A B C, that the beam of light entered it and left it at equal angles, and the deviation was consequently a minimum (§ 38), he found that the beam of refracted light formed an oblong image or spectrum, R V, containing seven colours, viz. red, orange, yellow, green, blue, indigo, and violet, the red being least and the violet most refracted from the original direction of the solar beam, S L E.

Agreeably to the received laws of refraction, Newton expected the image to be circular, like the white spot at E, which the sunbeam formed on the wall previously to the interposition of the prism, but when he found it to be five times longer than it was broad, it excited in him "a more than ordinary curiosity to examine from whence it might proceed."[1] It is unnecessary here to notice the different "suspicions," as he calls them, which he entertained on the subject. He at length determined beyond a doubt the true cause of the elongation of the coloured spectrum; namely, the fact that it consisted of a series of circular images, partly covering one another, and partly projecting one beyond another, from the red rays, which were least refracted, in succession, to the orange, yellow, green, blue, indigo, and violet, which last were most refracted. Hence he drew the grand conclusion, already enumerated (§ 3) as the fourth of the laws of light, namely, that light is not homogeneous, but consists of rays of different colours, and unequal refrangibility.

§ 69. *Rays of each particular colour not farther decomposable by refraction.*

It was not till Newton tried, by the test of experiment, every other hypothesis which suggested itself to his mind, and proved its fallacy, that he adopted the above conclusion as a true interpretation of the phenomena. Even after these rejections, his explanation had still to abide the sentence of an *experimentum crucis*, which was this. Having admitted the light and applied a prism as before, he received, at the distance of about twelve feet, the coloured spectrum on a board,

so perforated as to let pass one portion only of the decomposed beam. The coloured light which passed through was made to fall on a prism, and was afterwards received on the opposite wall, but it was found by this second refraction to be changed neither in colour nor in refrangibility. The rays which had been most bent by the first prism were most refracted also by the second; the image formed by the second refraction was of the same colour as the incident light, and circular.

§ 70. *Properties of the solar spectrum. Fraunhofer's fixed lines. Indices of refraction for the coloured rays. Mean ray.*

The colours of the solar spectrum, produced in the manner described by Newton, pass by insensible degrees into one another, so that it is difficult to assign to each its proper boundaries. Dividing the whole spectrum, however, such as was produced by the prism which he employed, into 360 parts, Newton determined the relative lengths of the coloured spaces to be as follows:—Red, 45; orange, 27; yellow, 40; green, 60; blue, 60; indigo, 48; violet, 80.

At the lower end, R, of the spectrum, the red light is comparatively faint, but grows brighter as it approaches the orange. The brilliancy increases to the middle of the yellow space, whence it gradually declines to the upper end, V, where it is extremely faint.

As rays of each colour proceed from every part of the sun's disc, there are formed in the spectrum of Newton a succession of coloured images overlapping one another, so that the different colours are not separated with that degree of purity which is attained, when a very fine line of solar light is viewed through a prism. When this is the case, the spectrum does not form a continued line of light, red at the one end, violet at the other, and fading by insensible degrees into all the intermediate tints, but is interrupted by perfectly dark lines of different breadths, which at various intervals cross the length of the spectrum at right angles. This fact was first noticed

by Wollaston in 1802. Fraunhofer, in 1819, without knowing what Wollaston had observed, discovered the same thing; but, instead of a few, he found, when he regarded the spectrum through a telescope, an infinite number of such lines or bands, as if rays of particular refrangibilities were absorbed in their course from the sun to the earth. Fraunhofer fixed upon seven principal and well-marked lines, which though they did not bound the different colours, yet served to identify certain points in the spectrum. By observing the refractive index for each of these *fixed lines*, as they are called, a much greater degree of exactness is attained in determining the refrangibility of the different rays.[2]

If the prism is of crown glass, the indices of refraction for the coloured rays are as follows:—Red, 1.5258; orange, 1.5268; yellow, 1.5296; green, 1.5330; blue, 1.5360; indigo, 1.5417; violet, 1.5466.

The green ray, *g* G, fig. 65, being midway between *g* R and *g* V, is called the *mean ray* of the spectrum. It is refracted from E to G, through an angle of deviation E *g* G, which is the mean refraction or deviation.

§ 71. *Recomposition of the prismatic colours into white light.*

Having clearly established the composition of white light, Newton also proved, experimentally, that all the seven colours, when again combined and made to fall upon the same spot, formed or recomposed white light.

He found, for instance, that the dispersed beam of light was recomposed, by placing close to the prism, A B C, fig. 65, a second prism, C A D, of the same material and same refracting angle as the first, but having its vertex in the opposite direction. The surfaces B A and C D being parallel, (§ 36,) the light passing through them was refracted contrary ways, and was returned by the second prism into a direction parallel to the direction S E, from which it had been bent by the first.

In another experiment, Newton received the spectrum upon a double-convex lens, of about three inches in breadth, and three feet radius, placed at the distance of four or five feet

from the prism. By this means, the coloured rays were made to converge to a focus, at a farther distance of ten or twelve feet. Intercepting the light, at that point, with a sheet of white paper, he found the colours mingled again into whiteness.

§ 72. *Dispersion by lenses. Chromatic aberration.*

As soon as the important truth was established by Newton, of the heterogeneousness of light, he saw that a lens, which, consisting of two inclined surfaces, refracts light exactly like a prism, must also refract the differently coloured rays in different degrees, so as to bring the violet rays to a focus nearer the lens than the red rays, in consequence of the former being more refrangible than the latter. Each of the two classes of lenses, the convergent and the divergent, is liable to disperse the rays of light, the one set while bending them inwards or lessening their previous divergence, the other while bending them outwards or lessening their previous convergence. (§ 42.)

A pencil of light falling on a convex lens is not in general refracted by it to a single point, for two reasons; *first*, the curvature of the refracting surfaces, and *secondly*, the unequal refrangibility of the differently coloured rays of which the pencil consists. Though these causes of aberration generally coexist, yet, being independent of one another, they may be examined separately. We have already considered the first; the effect of the second, to which we now proceed, being greatly more extensive, chromatic aberration forms a much more serious obstacle to the perfection of dioptric instruments than spherical aberration.

Let L L′, fig. 66, be a convex lens, and S L, S L′, rays of light falling upon it in parallel directions. The violet rays existing in the white light, S L, S L′, being more refrangible than the rest, will meet in a focus at *v*, forming there a violet image of the object from which the light proceeds. The red rays, which are the least refrangible, will be brought to a focus at *r*, and form there a red image of the object. The

index of refraction of the extreme violet rays for glass being

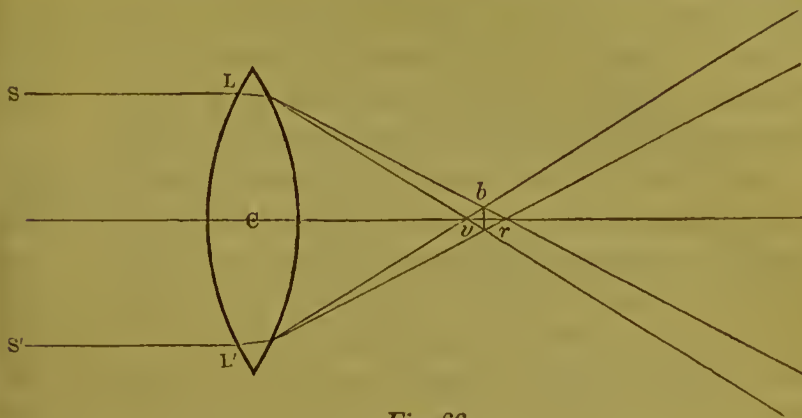


Fig. 66.

1.5466, and that of the extreme red rays 1.5258, C *v* will be the focal length of the lens for violet rays, and C *r* its focal length for red rays. The distance *v r* is called the *chromatic aberration* of the lens; and will be occupied by an infinite number of differently coloured foci. The violet ray from L′, and the red ray from L, intersect each other at *b*. A section of the emergent pencil at *b* is the smallest space through which the whole rays pass, and is called the *least circle of chromatic aberration*. It is nearly equidistant from *v* and *r*, and equals $\frac{1}{55}$ of the aperture of the lens. If the light emerging from the lens were received upon a screen, the central part only of the image would appear free from colour. If the screen were placed between *b* and C, the image would be fringed with red; if to the right of *b*, with violet.

Suppose L L′ to represent the crystalline, and that no correction of chromatic aberration took place in the eye, it is plain that were the retina placed at *r*, it would receive a picture of every external object tinged by all the prismatic colours; and the same, indeed, wherever it met the refracted and dispersed rays of light. The differently coloured rays come to focal points at unequal distances, and hence the image on the retina and the coincident impression would be confused and imperfect.

If we suppose L L′ to be the object-glass of a telescope, the eye-glass being placed to the right of *r*, and the eye looking through the eye-glass at the image formed by L L′, it is plain

that the eye could not see distinctly all the images formed between r and v. If it saw distinctly the yellow image formed near to b, it could not see distinctly either the red or the violet image. There would consequently be a distinct yellow image, with indistinct images in all the other colours.

Considering the great extent of chromatic aberration under such circumstances, it may seem strange that objects appear through a common telescope so distinct as they do. One cause of the confusion and indistinctness being so little, is, that the light is not scattered uniformly over the whole circular space occupied by the refracted rays, but is chiefly collected in the centre, and from the centre to the circumference is more and more rare, so that it is not strong enough to be visible, except in and near the centre. This must be the case in the eye, as well as in the telescope, and along with other causes enables us to see objects free from prismatic colouring.

§ 73. *Correction of chromatic aberration. Dispersive power not proportional to refractive power. Irrationality of dispersion.*

It has probably occurred to the reader, that, in the eye, where all the rays of light are refracted by the cornea and the crystalline, the same difficulty must be contended with as in the telescope or any other dioptric instrument. In the eye, the difficulty is some way or other obviated; for we see objects of their natural colours, and not surrounded by prismatic fringes, as we should certainly do, if some contrivance were not employed in the eye to prevent the chromatic aberration of the humours.

We have seen (§ 58, 59, 61, 62) that spherical aberration may be corrected in various ways. So may chromatic aberration. The circle of chromatic dispersion in any dioptric instrument is diminished, for example, by using a lens of a long focus. It was on this account that before the invention of the achromatic telescope, the excellence of telescopes depended in a great measure on the focal length of the object-glass. Huygens employed one whose focal length was 150

feet. Although the form of the eye excludes this mode of lessening chromatic aberration, a second mode is taken advantage of in the construction of this organ, namely, the diminution of its aperture by means of a diaphragm. The iris serves both to correct spherical aberration (§ 63), and to lessen the amount of chromatic dispersion.

These means, however, of correcting the chromatic aberration of dioptric instruments, are insignificant in comparison with another, to the discovery of which several individuals were led by reflecting on the achromatism of the eye.

When Newton transmitted a beam of light through several contiguous media, as water and glass, as often as by their contrary refractions, the light emerged in a direction parallel to its incidence, it appeared to him to be colourless; but if the emergent rays were inclined to the incident, the light was coloured. The conclusion which he drew from this experiment was, that the refraction of the different rays composing the prismatic spectrum was always in a given ratio to the refraction of the mean ray, whatever might be the refracting medium. "To the same degree of refrangibility," says he, "ever belongs the same colour, and to the same colour ever belongs the same degree of refrangibility." The cause of error in Newton's experiment cannot now be positively ascertained. The glass prism which he used may have been of a low refractive power; he may have increased the refractive power of the water by adding to it some saline ingredient, such as sugar of lead; or both such causes may have been acting together, so as to destroy the colour. Certain it is, that from the faultiness of the experiment, he was not only led to abandon the attempts in which he had been engaged to improve the refracting telescope, but missed one of the most useful optical discoveries.

Mr Hall, a private gentleman of Essex, the first who detected Newton's mistake, was led, we are told, while studying the mechanism of the human eye, to suppose, that could he find substances having such properties as he thought the humours might possess, he should be able to make an object-glass that would show objects colourless. After many experi-

ments, he had the good fortune to find these properties in two different kinds of glass, lenses of which compensated one another's dispersions, so that he succeeded in constructing an achromatic telescope.[3]

Euler, also, while he confessed that were Newton's ideas true in all their extent, it would be impossible to correct the refrangibility occasioned by the transmission of the rays from one medium into another of different density, maintained that such a correction was very possible, because he thought it actually effected in the structure of the eye, which he considered as formed of different media for that very purpose.[4]

Dollond, on repeating Newton's experiment of refracting a ray of light through a prism of glass, contained within a prismatic vessel of water, with their refracting angles in opposite directions, and so proportioned to each other, that the ray, after the opposite refractions, emerged parallel to the incident ray, found the ray very sensibly coloured. He concluded, that, if he could thus, by opposite refractions, produce colour, notwithstanding the parallelism of the incident and emergent light, he might by properly proportioning the refracting angles of his prism, effect an inclination of the refracted to the incident light, without dispersion. The event turned out as he expected; and pushing his experiments farther, he found, what had already been discovered by Mr Hall, that a colourless refraction might be produced not merely by a combination of two lenses with water between them, but of two lenses alone, formed of different kinds of glass.[5]

Newton showed that each of the component rays of light has a refrangibility different from the others; but had any one questioned him concerning the possibility of refracting light without dispersion, his reply would have been, that all his experiments, whether by single, or by opposite refractions, tended to establish the contrary conclusion. It was left to his successors to discover, that the refrangibility of the component rays differed according to the medium, and that among different media there existed a vast diversity in dispersive power. Similar prisms of different substances were known to

produce a different total amount of deviation, or, in other words, to have different refractive powers. Thus, such a prism as is represented in fig. 67, produces a greater *absolute* deviation of the whole body of light than that in fig. 68. But it was discovered by Hall and Dollond, that different substances cause the extreme rays of the spectrum to be separated in very different degrees, in proportion to their general refractive powers. Although the *absolute* deviation is greater in fig. 67, there is a greater *relative* deviation produced by the prism represented in fig. 68. A considerable number of highly refractive substances are also highly dispersive; but, in general, no inference regarding the *dispersive power* of any medium can be drawn from its refractive power.

Fig. 67.

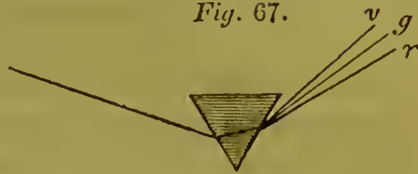


Fig. 68.

Again, although two media may differ in dispersive power, it by no means follows, that they cause the different rays of the spectrum to deviate in degrees proportional to the whole amount of dispersion. On the contrary, one medium, as in fig. 69, may cause the green ray, *g*, to take a position midway between the extremes *r* and *v*, while a second, fig. 70, may give it a position much nearer to the red, and a third, fig. 71, much nearer to the violet end of the spectrum. This fact constitutes what is called the *irrationality* of dispersion.

Fig. 69.

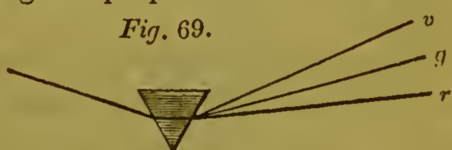


Fig. 70.

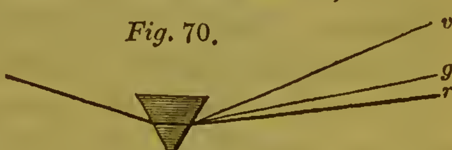
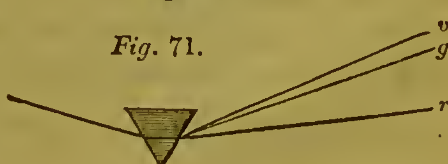


Fig. 71.



§ 74. *Measurement of dispersive power.*

Let s g E, fig. 72, be the direction of incidence of a ray of light on a prism, and g R, g V, the emergent red and violet rays; then the angle R g V, which is the difference between E g V and E g R, the deviations of those rays, is the *total dispersion.* If we increase the refracting angle, *a g b*, of the prism, we increase the mean refraction E g G, and the total dispersion, R g V. If we diminish the angle, the mean refraction and the total dispersion will diminish in the same ratio; but whatever be the angle of the prism, provided the material is unchanged, the total dispersion will always bear the same ratio to the mean refraction.

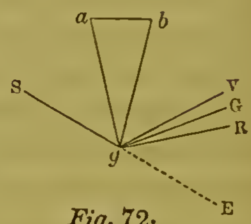


Fig. 72.

The *dispersive power* of a medium is measured by the rati of the total dispersion to the deviation of any particular ray, as the red. Thus, if of two different media there be formed prisms with equal refracting angles, and a ray of light be incident on each at a given angle, that medium has the greater dispersive power for which the ratio of R g V to E g R is the greater.

To express numerically the dispersive power of a medium, we divide the difference of its indices of refraction for the extreme violet and extreme red rays, by the excess above unity of its index of mean refraction. The index of refraction of the extreme violet ray for crown glass, being 1.5466, and that for the extreme red ray 1.5258, the difference of these indices, or .0208, would be a measure of the dispersive power of crown glass, if all bodies had the same mean refraction; but this not being the case, the dispersive power is measured by the relation between .0208 and .533, the excess above unity of its index of mean refraction. Thus, $\frac{.0208}{.533} = .03902$, the dispersive power of crown glass. The index of refraction of the extreme violet ray for diamond being 2.467, and of the extreme red 2.411, the difference of these is .056, nearly

three times greater than .0208, the same difference for crown glass; but then the excess above unity of the index of mean refraction for diamond, or 1.439, is also about three times greater than .533, the same excess in crown glass. Consequently $\frac{.056}{1.439} = .03892$, the dispersive power of diamond, is very little greater than that of crown glass. Hence, as Sir David Brewster[6] remarks, the splendid colours, which distinguish diamond from every other precious stone, are not owing to its high dispersive power, but to its great mean refraction.

The following table shows the difference of the indices of refraction of the extreme rays, and the dispersive power of some of the substances whose mean refractive powers are given in page 35, and of a few additional substances:—

	Difference of indices of refraction for extreme rays.	Dispersive power.
Fluor spar, . . .	.010	.022
Alcohol, ...	.011	.029
Sulphuric acid, . .	.014	.031
Plate glass, . . .	.017	.032
Water, . . .	.012	.035
Ether, ...	.012	.037
Olive oil, . . .	.018	.038
Diamond, . . .	.056	.038
Crown glass, . . .	.018	.039
Amber, ...	.023	.041
Oil of turpentine, . .	.020	.042
Zircon, ...	.045	.044
Flint glass, . . .	.029	.048
Muriate of antimony, . .	.036	.050
Oil of anise seed, . .	.044	.077
Sulphuret of carbon, . .	.077	.115
Phosphorus, . . .	.156	.128
Sulphur, after fusion, . .	.149	.130
Oil of cassia, . . .	.089	.139
Chromate of lead, least refraction,	.388	.262
" greatest refraction, estimated at	.770	.400

By far the most laborious and extensive inquirer into the dispersive powers of bodies is Sir David Brewster, to whose work on New Philosophical Instruments I must refer the reader, who is desirous of farther information on this subject. At present, I shall content myself with quoting the following abstract of his labours :—

The numbers in Sir David Brewster's table of dispersive powers, vary from .022, the dispersive power of eryolite, to .4, the estimated dispersive power of the greatest refraction of ehromate of lead ; an interval of surprising magnitude, and particularly interesting when we eonsider that Newton regarded all transparent bodies as possessing the same power of dispersion.

Chromate of lead, realgar, and phosphorus, whose dispersive powers are included between .4 and .128, must, from their chemical properties, be presumed likely to produce a great degree of dispersion ; but oil of cassia in this respect exceeds even phosphorus, stands far above every other animal or vegetable product, and exerts a most surprising influence in separating the extreme rays, thus indicating the existenee of some ingredient which chemieal analysis has not been able to deteet.

On comparing the refractive and dispersive powers of transparent bodies, it is difficult to ascribe the disparity of these powers to any general principle.

In two simple inflammable substances, sulphur and phosphorus, and in the metallic salts, a high refractive density is aceompanied with a high power of dispersion.

In the precious stones, on the contrary, a great refractive power, exceeding that of flint glass, is attended with a dispersive power generally much lower than that of water.

The dispersive powers of the resins, gums, oils, and balsams, greatly exceed that of water, and correspond in some measure with their powers of refraetion.

The different kinds of glass coloured with metals have a higher dispersive, as well as a higher refractive power, than flint glass.

Muriatic, nitric, and nitrous acids, have considerably higher

dispersive powers than water; while sulphuric, phosphoric, citric, and tartaric acids, which surpass the former in refractive density, possess very inferior powers of dispersion.

Fluor spar and cryolite, the only minerals in which fluoric acid is a principal ingredient, have the lowest dispersive powers of all bodies, and the lowest refractive powers of all solid substances.[7]

It would lead us too far from our subject, to describe minutely the modes in which the dispersive powers of refracting media are determined by experiment. Suffice it to say, that in one of the most frequently employed, the dispersive power of one substance formed into a prism, having been accurately determined, as a standard, the substance to be tried is shaped also into a prism, or enclosed within a hollow prism, and so placed that it refracts in opposition to the standard prism. An object seen through the two prisms appears coloured, till by turning round the standard prism in the plane which bisects its refracting angle, which is equivalent to actually varying this angle, the object appears colourless, the dispersion of the substance to be tried being corrected by that of the standard prism. From the position of the standard prism when this correction takes place, the dispersive power of the substance to be tried is readily deduced.[8]

§ 75. *Achromatic combinations.*

It has already been explained (§ 70), that the beam of light, dispersed by refraction, is recomposed, by placing close to the prism A B C, fig. 65, a second prism, C A D, of the same material, and having the same refracting angle as the first, but with its vertex turned in the opposite direction. Let the prism A B C be of crown glass, and the prism C A D be of flint glass, taking care that the refracting angles of the two are so proportioned, that, when tried separately, they produce a spectrum of precisely the same length, which will require the angle of the flint glass prism to be less than that of the crown. The separation of the rays of light which would be produced by the prism A B C, will be so far corrected by the prism C A D,

that the beam being refracted to a point E′, above E, will form there a round spot, almost free from colour.

In this experiment, though the total dispersion produced by the two prisms of different materials are equal and opposite, and thus the extreme red and violet rays are united in the emergent beam, there is still, in consequence of the irrationality (§ 73) of the coloured spaces of the spectrum, a dispersion of the intermediate rays; the middle or green rays being more refracted, in proportion to the extreme rays, by the one prism than by the other. The beam, therefore, instead of emerging colourless from the two prisms, as was the case when two equal prisms of crown, or two equal prisms of flint glass were employed, forms at E′ a faint *secondary spectrum*, tinged on one side with purple, and on the other with green light.

Were three media employed for the purpose of uniting three rays, for instance, the red, green, and violet, ther would still arise in like manner a *tertiary spectrum*, from the want of union of the other rays in the emergent beam, so that in theory it seems impossible to attain a perfect correction of colour. After a few combinations, however, the spectra are so small and faint, as to be insensible.

To apply these principles of achromatic compensation to lenses, let L L, fig. 73, represent a double-convex lens of

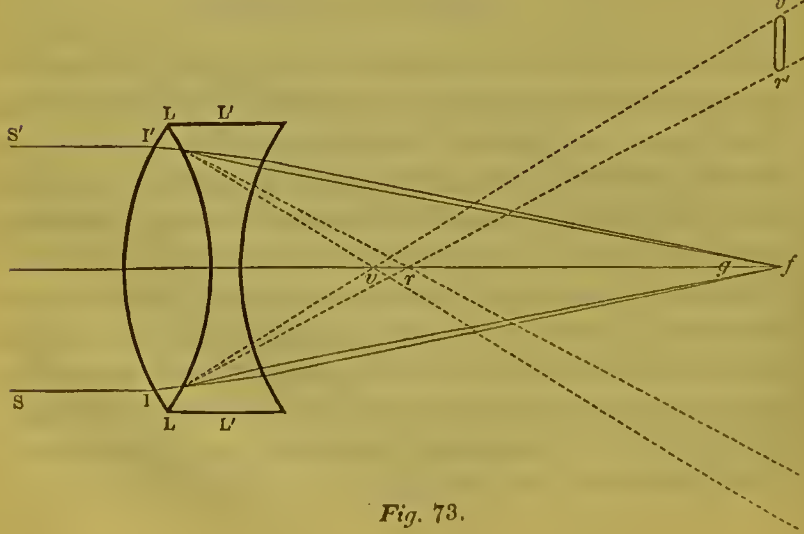


Fig. 73.

crown glass, and L′ L′ a double-concave one of flint glass. A ray of solar light, S I, falls at I on the convex lens, which will refract it exactly as a prism would do, whose surfaces were tangents to the lens at the points where the ray enters and quits it. We shall suppose that the solar ray, S I, thus refracted and dispersed by the lens L L, would have formed a primary spectrum, $v' r'$, had there been no other lens to correct the dispersion, the violet ray, I v', crossing the axis of the lens at v, and going to the upper end of the spectrum, and the red ray, I r', going to the lower end. In the figure, the degree of dispersion is greatly exaggerated. The flint glass lens, L′ L′, being of greater refractive density than the crown glass lens, L L, its curvatures must be so proportioned, that the focus of the two lenses shall be at f, where, from the greater dispersive power of the flint glass lens correcting the dispersion of the crown glass lens, the decomposed rays, I v', I r', will be reunited, and their colour destroyed. To produce this effect, it is requisite that the focal lengths of the two lenses be to each other in the ratio of their dispersive powers; that is, the ratio of the dispersive power of the flint glass lens being to that of the crown as 1 to d, the focal length of the flint to that of the crown must also be as 1 to d, the lenses being in contact. The solar ray S I has thus been refracted by the double achromatic lens L L, L′ L′, from its primitive direction, S I, into the new direction I f. In like manner, the corresponding ray S′ I′ will also be refracted to f, where an image of the sun will be formed, not absolutely colourless indeed, but with a great diminution of chromatic aberration.

Were a double object-glass, consisting, as we have now been supposing, of a concave lens, which disperses the rays in a greater degree, and a convex, which disperses them in a less degree, turned towards such an object as a well defined white circle on a black ground, the great mass of the orange and blue rays would be collected in a focus at f; but there would always be found, when the correction of colour was as perfect as such an object-glass could render it, a fringe of green on the interior edge of the circle, and a fringe of purple

on the exterior. The fringe of purple is formed by a union of the red and violet rays; the green fringe is composed in part of the homogeneal green rays, and in part by a union of the yellow and blue rays. Such a lens then, is only comparatively, not absolutely, *achromatic*.[9]

To the ingenuity of Dr Blair,[10] we owe the discovery of a method of getting rid of the secondary purple and green fringes. Having observed that when the extreme red and violet rays were perfectly corrected, the green were left out, the red and violet rays, I v, I r, being united at f, while the green rays were more refracted and crossed the axis at g, he conceived the idea of combining two achromatic lenses, the one concave and the other convex, both of which should refract the green rays less than the united red and violet. As the convex lens was to refract the green rays *to* and the concave one to refract them *from* the axis, it followed, that by a combination of these opposite effects, the green rays would be united with the red and the violet. Dr Blair's achromatic convex lens was formed of two essential oils, such as naphtha and oil of turpentine, which differ considerably in dispersion, and his achromatic concave lens of the more dispersive oil and glass. When the two were placed together, an excess of refraction remained in favour of the convex combination, but the secondary spectra of each, being equal and opposite, were totally destroyed.

In the prosecution of his researches, Dr Blair was farther led to the knowledge of the possibility of forming binary combinations, having secondary spectra of opposite characters, that is, that while in some combinations the green rays were more refracted than the united red and violet, in others they were less. At last he discovered a means of producing by a single binary combination, a refraction absolutely colourless. Having found that muriatic acid had the property of producing a primary spectrum, in which the green rays were among the more refrangible, to increase its refractive and dispersive power, he mixed it with muriate of antimony. He thus succeeded in obtaining a spectrum which presented the same proportion of the coloured spaces as that formed by crown-

glass. By enclosing, therefore, this fluid between two convex lenses of crown-glass, Dr Blair was able to refract parallel rays to a single focus, without the least trace of chromatic aberration.

The construction of fluid object-glasses has been prosecuted by Mr Peter Barlow, on a plan different from that of Dr Blair, so as to effect the corrections of chromatic and spherical aberrations in the passage of the rays through the fluid, which is sulphuret of carbon, and making them impinge perpendicularly on the last surface, so that they are thence transmitted aplanatic to the focus.

Triple achromatic object-glasses are sometimes constructed, so as to divide the refraction between two double-convex lenses, the one of crown and the other of plate glass, with a double-concave of flint glass between them; but a double glass is generally preferred; the one of its lenses being an unequal double-convex of crown glass, and the other a concavo-convex of flint glass. Whatever be the combination adopted to produce the correction of colour, care is taken at the same time to ensure the destruction of spherical aberration, by properly proportioning the curvatures. The correcting lenses need not be placed close together; practical advantages are sometimes gained by separating them by certain intervals.

§ 76. *Is the eye achromatic?*

The obvious answer to this question seems to be, that in the ordinary exercise of vision, we do not see objects tinged with chromatic fringes. So long as the eye is able to accommodate itself to the distances of objects, and is allowed to do so, and so long as the mean rays of direct central pencils converge accurately upon the retina, no prismatic colours are perceptible. Therefore, it is concluded, the eye is achromatic.

"The eye," says Mr Coddington,[11] "when employed in its natural and proper manner is achromatic: pencils of the most opposite colours are brought to their respective foci with equal accuracy, as may be observed by looking at any varie-

gated object; and this is true, however rapidly the eye be directed from one colour to another, and even when they are so intermixed as necessarily to be seen together, so that it need not be supposed that any alteration in the form of the eye takes place. As to pencils entering the eye obliquely, it is true that they are not refracted so as to produce distinct vision, at least when the obliquity is considerable, but neither in that case is there any appearance of coloured fringes about the edge of an object."

The negative, however, has been asserted on the following grounds:—

1st. That experiments show that the dispersion of colours in the eye is not corrected.

2d. That from the construction of its media, it cannot be achromatic.

3d. That it does not require to be achromatic to produce distinct vision.

"I consider the *non-achromatism of the eye*," says Sir David Brewster, "as a fact as well established as any other fact in natural philosophy."

§ 77. *Experiments adduced to prove that the dispersion of the eye is not corrected.*

1. Those who maintain that the eye is achromatic will readily admit such facts as the following, but will offer a different explanation of them from that of Dr Blair, Sir David Brewster, and others, who advance them as proofs that the dispersive power of the media of the eye is uncorrected.

If one looks at the bar of the window, and holding the hand parallel with the bar, bring the hand slowly over the eye, just before the bar disappears, one side of it will appear edged with red and the other with blue. A distinct prismatic spectrum may be seen by shutting up all the pupil except a portion of its edge, or looking past the finger held near the eye, till the finger almost hides a narrow line of white light. If we accommodate the eye to a distant object, a near object appears surrounded by a red penumbra, inclining to orange,

and, on the other hand, if the eye is accommodated to a near object, distant objects, such as the bar of the window, are surrounded by a blue penumbra. To a near-sighted eye, a small bright object on a dark ground appears edged with colour, the effect being rendered more conspicuous by using a blue glass, which allows the extreme rays of the spectrum to pass; but stops or weakens the middle rays.

To those who cite such experiments as proofs of the dispersion of the eye not being corrected, it is replied, that though the eye may be perfectly achromatic for direct central rays, it does not follow that it must be so for oblique eccentrical pencils; that by certain arrangements vision may be so modified, that an actual dispersion takes place on the retina, although this is quite insufficient to prove that the eye in ordinary circumstances is chromatic; that the mechanism of the eye is very likely to prevent chromatic aberration in the ordinary circumstances of vision, without providing against dispersion in all possible cases; that it is only when the eye is adapted to bring the pencils to foci on the retina, that the achromatism of the eye is likely to be preserved; that the correction of colour in the eye probably depends on arrangements infinitely finer than those of any instruments of human construction, and may, therefore, be disturbed in such experiments as the above; and that many individual eyes may not be achromatic, for if the dispersive powers of the media vary ever so little, the achromatic adjustment may be destroyed. It is also urged that when an object is placed in a very small beam of light, its shadow is bounded by a series of coloured fringes, a phenomenon known by the name of *diffraction* of light; that when two portions of light, one reflected from a slender body, and the other bending round it, *interfere*, in the optical sense of the term, the appearance of coloured fringes is produced still more distinctly; and that such phenomena are extremely likely to take place in some of the experiments above mentioned.

2. Dr Wollaston mentioned to Dr Young[12] an experiment, which he thought proved an uncorrected dispersion in the eye. The observer looks through a prism at a small lucid

point, which of course becomes a linear spectrum. The eye, it is asserted, cannot so adapt itself as to make the whole spectrum appear a line; for, if the focus be adapted to collect the red rays to a point, the blue will be too much refracted, and expand into a surface; and the reverse will happen if the eye be adapted to the blue rays; so that, in either case, the line will be seen as a triangular space.

On repeating this experiment with my right eye, which has become presbyopic, the spectrum has always appeared to me dilated towards the red and tapering towards the blue, while with my left eye, which has always been myopic, the sides of the spectrum appear parallel. With neither eye, have I ever been able to observe the red portion to become contracted when I regarded the blue portion, nor *vice versa*. Several of my friends have also repeated the experiment, without observing any alternate dilatation and contraction, according as the one end or the other of the spectrum is regarded.

3. Fraunhofer admitted the different prismatic rays successively into a telescope, and found it necessary, in passing from the red to the violet ray, to adjust both the eye-glass to the object-glass, and the eye-glass to the micrometer-wire, in order to see the wire distinctly in the different sorts of light. The whole displacement, Professor Powell remarks,[13] must be the sum of the chromatic aberrations of the object-glass, the eye-glass, and the eye. Fraunhofer does not notice the first; says that the second is allowed for; and takes the residuum as the dispersion of the eye. He elsewhere states that the telescope was not perfectly achromatic; and as the data are not stated, the inference cannot be regarded as conclusive, and Fraunhofer admits that it is not precise.

Professor Powell has tried similar experiments, but found the displacement so small, that he is quite in doubt whether any was requisite. Considering that the aberration of the lenses may be uncertain to a larger amount than the quantity sought, it cannot be satisfactorily deduced by this method.

§ 78. *Does the construction of the eye admit of achromatism?*

A notion advanced by Dollond,[14] and adopted by Wells and others, was, that the refractions at the several surfaces of the media of the eye, are all made the same way, and consequently, that for want of contrary refractions, the colours produced at the first surfaces cannot be destroyed by the subsequent ones.

Sir David Brewster, commenting[15] upon this opinion, asserts that "the refractions are not all performed one way. The vitreous humour" says he, "acts as a concave lens, and the rays are refracted *from* the axis in passing from the capsule of the crystalline into the vitreous humour." He adds, however, that "the refractive and dispersive powers of the crystalline and vitreous humour are such that an achromatic compensation is impossible."

In these remarks of Sir David Brewster, we meet with two assertions, which seem to require some modification.

With respect to the refractions produced by the lenses of the eye, it must be observed, that while the rays refracted by the cornea, on quitting its posterior surface to enter the aqueous humour, suffer a certain trivial decrement of their convergence, the rays which quit the posterior surface of the crystalline, to enter the vitreous humour, undergo a new refraction *towards* the axis. The deviation which occurs at the posterior surface of the cornea being almost inappreciable, it is not likely that any correction of chromatic dispersion takes place there; while, from the deviation at the posterior surface of the crystalline being towards the axis, it is demonstrable that no correction can take place there *on the principle of opposing refractions.*

Dollond could not conceive that prismatic colours could be corrected by refractions which are all performed the same way; but the subsequent investigations of Dr Blair[16] plainly showed, that in this notion Dollond was mistaken, and that the refractive densities and dispersive powers of two or more media might be so proportioned, as to refract in one and the

same direction, without dispersion. Dr Blair, therefore, had no hesitation in deciding, that "the aberration from difference of refrangibility might have been removed, by imparting a proper degree of dispersive power to the vitreous humour;" although, misled by such experiments (§ 77) as show a coloured penumbra surrounding the edges of objects placed either within or beyond the distance to which the eye is accommodated, and regarding any correction of chromatic aberration "unnecessary for the common purposes of life," he concluded, that no contrivance for this purpose had been introduced in the structure of the eye.

It being perfectly conceivable, then, that nature might have corrected the chromatic aberration of the lenses of the eye by proportioning the refractive and dispersive powers of the vitreous humour to those of the crystalline, and those of the dense laminæ of the crystalline to those of the less dense, without contrary refractions, the impossibility of an achromatic compensation in the eye, alleged by Sir David Brewster, must be tried entirely by a still more careful examination of the optical properties of the humours than has yet been made.

Whether they admit or deny the *fact* of the achromatism of the eye, almost all writers represent it as a thing impossible in strict theory; so that those who attempt to explain it, do so generally by means of some supposed modification of light, of a nature different from those with which we are actually acquainted, and not by any strict theoretical principle. Professor Powell, however, has endeavoured to show that as an abstract problem, and in strict theory, such a combination as that which exists in the eye may be accurately achromatic. "I have shown" says he, "in a way which can only be refuted by disproving the whole established theory of foci and refractive indices, that, as far as theory is concerned, achromatism is perfectly obtained, in a combination of a lens and one medium, if only the indices and radii fulfil the conditions of a certain formula. I have also shown by observation, that in the particular instance of an ox's eye the indices are as nearly as possible in the required ratio."[17]

It appears to be Professor Powell's opinion, that the achromatism of the eye may be produced by the nature of the medium, in which the focus is formed, which is the same principle on which Sir David Brewster constructed an achromatic microscope, for examining objects immersed in a fluid.[18] Sir David acknowledges the similarity of principle between his microscope and the alleged achromatic compensation in the eye, but insists that in practice it is very different.[19]

§ 79. *Does the actual distinctness of vision require the eye to be achromatic?*

"The idea" says Sir David Brewster,[20] "that the eye would answer the purposes of vision more perfectly if it were achromatic, seems to be founded on a hasty analogy. Because an achromatic telescope, or microscope, or lens, is preferable to the same instruments when they are not freed from colour, it is conceived that an achromatic eye should have the same superiority; the two cases, however, are considerably different. In using the telescope, &c. the eye views in succession every part of the image which they form, in every part of the object within the field of view; but there is no eye behind the retina to view in the same manner the image which is formed upon that membrane. In point of fact, *the eye is incapable of seeing any object distinctly* unless *it is situated in or near its axis*, and hence it is of no importance whatever to render the image distinct at a distance from the axis. Whenever the eye wishes to examine an object, or a part of an object, minutely, it instantly directs to it the axis of its vision, and from the rapidity of its movements, and the duration of the impressions of light, it thus obtains the most perfect view of a given object, and can scrutinize in succession its minutest parts.

"Now in order to obtain distinct, and a *sensibly colourless* vision, near the axis of the eye, achromatic compensation is not necessary. In order to prove this, look through a convex lens, about an inch in focal length, at any sharp and well-defined dark object on a luminous ground, and the most perfect

and colourless vision of this object will be obtained in and near the common axis of the eye and the lens. Now in this case we have *sensibly colourless* vision, although the lens is not achromatic, and although its achromatic aberration is increased by whatever colour there may be in the eye itself. How much more, then, should vision be *sensibly colourless near the axis of vision*, and with the eye alone, when we consider that it is composed of substances which have a much lower dispersive power than glass!"

In these remarks, Sir David Brewster fails to point out any essential difference between the eye and other dioptric instruments, in regard to the advantage to be gained by their being achromatic. If diffusion and colour are injurious to distinctness in the one case, they will be so in the other also. True, there is no eye behind the retina; the retina is the eye, and according as the rays are brought to exact focal points, or spread out into diffused and coloured spaces, objects will be perfectly or imperfectly seen, both in and out of the axis of vision.

The experiment with the lens is inconclusive. No doubt when we look through the axis of a common lens, at an object placed within the principal focal length, no prismatic colours are seen edging the object. The sensible colourless vision, in this case, may be attributed partly to the extreme minuteness of the coloured fringes which are formed by the dispersion of the central portion of a lens, and partly to the degree of colour which is actually produced being corrected by the eye. If the chromatic aberration of the lens were increased by an uncorrected dispersion in the eye, it is probable that vision through the lens would be sensibly coloured.

As the most probable means of clearing up the difficult question we are now considering, Dr Maskelyne[21] proceeded to calculate the dispersion of light in the human eye.

For this purpose, he took the dimensions of the eye from Petit, as related by Jurin. The refraction of the vitreous humour of an ox's eye having been found by Hauksbee to be the same as that of water, and the ratio of refraction out of air into the crystalline of an ox's eye having been found by

the same experimenter to be as 1 to .68327, Dr Maskelyne assumed the refraction of the mean refrangible rays, out of air into the aqueous or vitreous humour, the same as into water, as 1 to .74853, or 1.33595 to 1; and out of air into the crystalline as 1 to .68327, or 1.46355 to 1. With these data, he infers from Newton's theorems on dispersion, that the ratio of refraction of the most, mean, and least refrangible rays at the cornea should be as 1 to .74512, .74853, and .75197; at the fore-surface of the crystalline as 1 to .91173, .91282, and .91392; and at the hinder-surface of the crystalline as 1 to 1.09681, 1.09550, and 1.09420.

"Now, taking with Dr Jurin 15 inches for the distance at which the generality of eyes in their mean state see with most distinctness, I find" says Dr Maskelyne, "the rays from a point of an object so situate will be collected into three several foci, *viz.* the most, mean, and least refrangible rays at the respective distances behind the crystalline .5930, .6034, and .6141 of an inch, the focus of the most refrangible rays being .0211 inch short of the focus of the least refrangible." He does not give the steps by which he arrives at this result, nor the data, founded on the length of the axis of the eye and the radii of curvature of the media, necessary for solving the problem.

"Moreover," he continues, "assuming the diameter of the pencil of rays at the cornea, proceeding from an object at 15 inches distance, to be $\frac{1}{5}$th of an inch in a strong light, which is a large allowance for it, the semi-angle of the pencil of mean refrangible rays at their concourse upon the retina will be 7° 12′, whose tangent to the radius unity, or .1264 multiplied into .0211 inch, the interval of the foci of the extreme refrangible rays, gives .002667 inch for the diffusion of the different coloured rays, or the diameter of the image of the indistinct circle upon the retina. Now, I find, that the diameter of the image of an object upon the retina is to the object as .6055 inch to the distance of the object from the centre of curvature of the cornea; or the size of the image is the same as would be formed by a very thin convex lens, whose focal distance is .6055 inch, and consequently a line in

an object which subtends an angle of 1′ at the centre of the cornea will be represented on the retina by a line of $\frac{1}{5678}$th inch. Hence the diameter of the indistinct circle on the retina before found, .002667, will answer to an external angle of $.002667 \times 5678' = 15' 8''$, or every point in an object should appear to subtend an angle of about 15′, on account of the different refrangibility of the rays of light."

Dr Maskelyne next endeavours to show that this angle of ocular aberration is compatible with the actual distinctness of vision. With this view, he compares the supposed dispersion in the eye to that in the common refracting telescope. In the latter, the angular indistinctness is known to amount to 57′; in the eye, it is only 15′, that is nearly four times less. "Consequently" says he, "the real indistinctness, being as the square of the angular aberration, will be 14 or 15 times less in the eye than in a common refracting telescope, which may be easily allowed to be imperceptible."

Newton observed, with respect to the telescope, that the erring rays are not scattered uniformly over the circle of dissipation in the focus of the object-glass, but collected infinitely more densely in the centre than in any other part of the circle. (§ 72.) He farther observed, that the most luminous rays are not those of *mean* refrangibility, in the confine of green and blue, but the middle of the orange and yellow (§ 70); a fact, which should lead us to infer that the dispersion of those rays which are *effectively* luminous, is not so great as is above assumed. From these considerations, Newton calculates that the dispersion of the light which is effective is to the whole dispersion only as 55 to 250, *i. e.* if the diameter of the circle of dissipation of the whole rays be 250, that of the rays which are sufficiently luminous to make an impression will be only 55. Applying this reasoning to the eye, Dr Maskelyne infers that if the whole dispersion equals 15′, that of the effective light will be only 3′ 18″.

It follows from this, that Dr Maskelyne admits an effective aberration of 3′ 18″. A fixed star, therefore, should appear to have a diameter of 3′ 18″. Dr Maskelyne says that the brightest fixed stars have, he thinks, a visible diameter equal

to about one half of that quantity, and this he considers a sufficiently near coincidence with his theory. "This reduced angle of aberration" says he, "may perhaps be double the apparent diameter of the brightest fixed stars to an eye disposed for seeing most distinctly by parallel rays; or, if short-sighted, assisted by a proper concave lens; which may be thought a sufficient approximation in an explication grounded on a dissipation of rays, to which a precise limit cannot be assigned on account of the continued increase of density from the circumference to the centre. Certainly some such angle of aberration is necessary to account for the stars appearing under any sensible angle to such an eye." On the same principle he explains how the smaller stars have a less apparent diameter; for the whole light being faint, it will only be the portion still more condensed towards the centre that can be noticed.

Such is an abstract of Dr Maskelyne's paper. He does not point out any definite experiment to prove that the actual distinctness of vision corresponds with his conclusions. It obviously follows, however, from his statement, that a luminous point should appear as a circle having a diameter equal to $3' \ 18'' = 200''$, *i. e.* equal to $\frac{1}{9}$ of the diameter of the moon. A fixed star appears to Dr Maskelyne to have a diameter of about $100''$, *i. e.* $\frac{1}{18}$ of the diameter of the moon, and he thinks this a near enough coincidence to establish his point.

The justness of his conclusion, however, may be doubted for the following reasons:—

1. Because he underrates the extent of the circle of effective aberration.

2. Because it is by no means proved, that the apparent diameter of the fixed stars arises from chromatic aberration. It is more likely to arise, as Jurin supposed, from a difficulty in accommodating the eye to distances.

3. Because the apparent diameter of a fixed star never is so much as $100''$, *i. e.* $\frac{1}{18}$ of the diameter of the moon.

4. Because, though it were, the supposition would not agree with the theory, which requires that it should be $200''$.

5. Because a fixed star, being a visual point, ought to be

surrounded by a coloured halo, instead of presenting a uniform colour, which it does.

6. Because the moon should always, on the same principle, be seen with an indistinct halo or ring, 100″ in breadth, and this should be very evident when we screen the moon from the eye, and look at its edge.

But it is a much more unexceptionable plan, to make experiments on lines or points, placed at moderate distances from the eye. According to Dr Maskelyne's conclusion, two points placed so that the interval between them subtends 3′ 18″ at the eye should appear as two circles touching each other, and two parallel lines the distance between which subtended 3′ 18″, should be confounded together into one broad space. Now, 3′ 18″ are to the radius as 1 to 1040. Therefore, if the distance between two parallel lines is not more than $\frac{1}{1040}$ of their distance from the eye, they should appear to form one confused space and not two distinct lines. Therefore, two lines $\frac{1}{10}$ inch asunder and 104 inches from the eye should, according to Dr Maskelyne, appear confused, which is not found to be the case.

Dr Rainy informs me, that he has calculated the dispersion for a ray of white light, falling on the cornea parallel to the axis of vision, and at the distance of 1 line from the axis. The following is the result:—

If the radius of curvature of the cornea be $3\frac{1}{2}$ lines, then this ray will fall on the cornea at an incidence of 16° 36′; for $3\frac{1}{2} : 1 :: 1 : 0.2857 =$ sine of 16° 36′. Suppose, for simplicity, the mean index of refraction of the eye to be the same as that of water, 1.336, and the difference of the indices of refraction for the extreme rays to be 0.012, then the index for the red ray will be 1.330 and for the violet ray 1.342.

Sine of incidence,	0.2857.	Angle of incidence of incident ray,	16° 36′
Sine of refraction of red ray,	0.21481.	Angle of refraction of red ray,	12° 24′ 15″.
... ... violet ray,	0.21289.	... ... violet ray,	12° 17′ 30″.
			6′ 45″.

Consequently, the violet rays form an angle of 6′ 45″ with

the red rays. Whence, if the red rays at this incidence come to a focus, the other rays will occupy a circular area of 6′ 45″ radius or 13′ 30″ diameter. From this it follows, that a physical white point would be projected on the retina as a circular area of this diameter, with the red in the middle, and the other colours in concentric circles. A minute white spot on a black ground would consequently be seen with a diameter of 13′ 30″ greater than its true diameter.

It follows from this, that two white points or white lines on a black ground, at such a distance from one another as not to subtend more than 13′ 30″ at the eye, should appear confused together, if the eye is adapted to produce the convergence of the extreme red rays; or when their distance subtends 6′ 45″, if the eye is adapted to produce the convergence of the rays of mean refrangibility. Now 6′ 45″ is equivalent to $\frac{1}{510}$ of the distance from the eye. In other words, two white objects, on a black ground, and removed from one another $\frac{1}{510}$ of their distance from the eye, ought to be confused together, on the supposition that there is no correction of colour.

Now, Dr Rainy finds that two lines distant from one another $\frac{1}{100}$ inch, can be distinguished as separate lines at 35 inches from the eye; that is when the distance between the lines is $\frac{1}{3500}$ of their distance from the eye, and subtends at the eye an angle of 1′. It follows that the distinguishing power of the eye has a limit of 1′, instead of the limit 6′ 45″, which is deduced from the supposition that there is an uncorrected dispersion in the eye, equal to that of water.

If the chromatic aberration were a little less than 1′, then its existence without correction would be perfectly consistent with the actual distinguishing power of the human eye. But the distinguishing power actually ascertained cannot be reconciled with the calculated aberration of 6′ 45″, nor even with the aberration of 3′ 18″, admitted by Dr Maskelyne.

That the eye, then, may be regarded as certainly achromatic, appears proved by our seeing two points, or two lines, distinct and free from colour, when subtending at the eye an angle of more than 1′.

In an artificial eye, having the same curvatures and the

same refractive densities as the natural eye, the images of these points and lines, if viewed with a magnifier, would appear coloured, the rings being too minute to be otherwise discerned. By what means it is that they are not produced in the living eye, or, if produced, are not discerned, is unknown.

§ 80. *Achromatism of the eye hitherto unexplained.*

The media of the eye present such slight differences of refractive and dispersive power, that we cannot account for its achromatism on any known optical principle. We may surmise that a compensation takes place between the refractions at the cornea and the crystalline, or that the varying density of the crystalline serves to correct chromatic, as well as spherical, aberration; we may conjecture that perhaps by proportioning the curvatures of the media to each other, nature may have been able to counteract dispersion in the eye; but in the present state of our knowledge, we can offer no satisfactory theory on the subject.

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[1] Philosophical Transactions, abridged by Lowthorp, i. 128.

[2] Edinburgh Philosophical Journal, ix. 288; x. 26; Edinburgh 1823, 1824.

[3] Philosophical Magazine, November 1798, 177.

[4] Histoire de l'Académie Royale des Sciences pour 1747, 379; Berlin 1749.

[5] Philosophical Transactions for 1758, 733.

[6] Treatise on Optics, 77; London 1831.

[7] Brewster's Treatise on New Philosophical Instruments, 310; Edinburgh 1813.

[8] Ib. 294.

[9] *Achromatic,* from α privative, and χρῶμα, *colour.*

[10] Transactions of the Royal Society of Edinburgh, iii. 3; Edinburgh 1794.

[11] System of Optics, Part ii. 5; Cambridge 1830.

[12] Philosophical Transactions for 1801, 50.

[13] Report of the third meeting of the British Association, 374; London 1834.

14 Peter Dollond's Account of the Discovery made by John Dollond, which led to the grand improvement of Refracting Telescopes, 6; London 1789.

15 London and Edinburgh Philosophical Magazine for March 1835, 163.

16 Op. Cit. 19.

17 London and Edinburgh Philosophical Magazine for April 1835, 247. Report of the third meeting of the British Association, 376; London 1834. Report of the fourth meeting of the British Association, 548; London 1835.

18 Brewster's Treatise on New Philosophical Instruments, 401; Edinburgh 1813.

19 London and Edinburgh Philosophical Magazine for March 1835, 163.

20 Ib.

21 Philosophical Transactions for 1789, 256.

CHAPTER XI.

DISTANTIAL ABERRATION. ADJUSTMENT OF THE EYE TO DISTANCES.

§ 81. *Distantial aberration explained. Circle of aberration.*

The focus of a convex lens, or set of lenses, is more remote, in proportion as the rays which fall upon it are more divergent; or, in other words, proceed from nearer objects. (§ 43.) Thus, rays proceeding from any point of an object infinitely distant, are parallel, as in fig. 74, and, by a convex lens, are

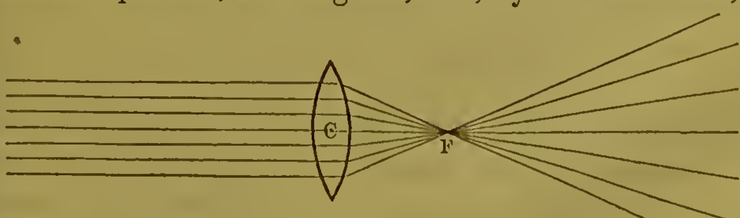

Fig. 74.

speedily united at the principal focus, F. If the object ap-

proaches the lens, so that the rays emanating from any point of it are no longer parallel, but diverge, as in fig. 75, the focal

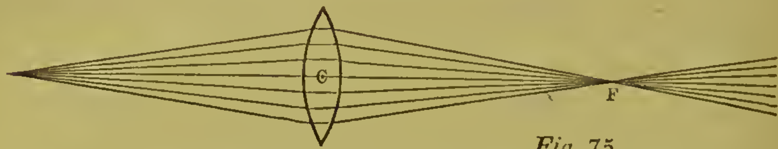

Fig. 75.

distance, C F, is lengthened. In proportion as the object is brought nearer, and the rays consequently fall upon the lens with an increasing degree of divergency, the focal distance, C F, becomes still greater, as in fig. 76, till, at length, if the

Fig. 76.

distance of the object is just equal to the principal focal length of the lens, the emerging rays become parallel, and consequently never come to a focus. The nearer the object, the greater the divergency of the incident rays; and the greater their divergency, the more distant their focus.

If the form and situation of all the parts of the compound lens, constituted by the refractive media of the eye, remained perfectly unaltered, it is plain that only those rays which diverged from points at a particular distance, could be collected into foci on the retina. Thus, if the image of Q, fig. 77,

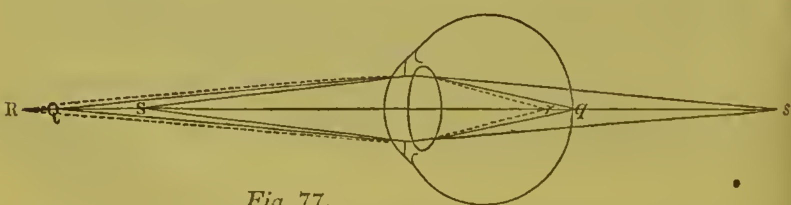

Fig. 77.

were formed exactly on the retina at *q*, the image of R, a point farther from the eye than Q, would be formed within the eye, at *r;* whence the rays, again diverging, would be diffused over some space on the retina, forming there a luminous spot, a *circle of dissipation* or *aberration*, so that if the

rays proceeding from the points in the object, necessary to be distinguished from R, formed similar spots, the spots from different points would mix, and the vision of the object, or of any particular point in it, would be indistinct. On the other hand, the rays which diverge from S, a point nearer than Q, would after refraction converge toward *s*, a point behind the eye, and, would therefore occupy in their course a circular space on the retina, so that the perception of S would be indistinct, like that of R.

On the supposition that the eye admitted of no adjustment to distance, there could be only one distance at which objects could be seen perfectly. The rays, proceeding from objects nearer than that distance, would be intercepted by the retina, before they could unite into focal points; while those proceeding from more remote objects would reach the retina only after they had crossed each other, in a focus anterior to the retina. In either of these two cases, each pencil would throw upon the retina a small circle of light, brighter at the middle, and fainter at the edge, which would overlap the circles formed by the adjacent pencils, and thus create, by what we may term *distantial aberration*, a confusion in the image and an indistinctness of vision.

To form a notion of distantial aberration, and of the confusion arising from it, hold a convex lens, which may be supposed to represent the eye, towards two lighted candles, and receive the images on a sheet of paper, at such a distance as allows the images to be distinct. If the lens and sheet of paper are kept steadily at the same distance from one another, and either brought nearer to the candles or removed farther from them, the images will become diffused and indistinct; the space between them, compared to the space between the candles, will be disproportionally contracted, and at length the images will coalesce and overlap each other. The same sort of confusion and indistinctness would occur with the images on the retina, were this sort of aberration not corrected by the mechanism of the eye.

§ 82. *Difference of perfect, distinct, and indistinct vision.*

From what has been stated above, the reader might perhaps be led to suppose, that in order to see any object, such as the letters of the printed page before him, it would be necessary that all the rays of a pencil flowing from any point of the object, should be united in a point on the retina. There is no doubt, that vision will be most distinct, when the rays of each pencil are brought to corresponding focal points; and hence Jurin[1] called this *perfect vision;* but it is easy to show that we may discern objects, with a considerable degree of distinctness, when there is no such exact union of the rays on the retina.

Turn to the title-page, in which there are letters of three or four different sizes, and place the book at such a distance that every size appears distinct, without any straining of the eye, which will be about the distance of 12 inches. In this case, it may be presumed, that the rays of every pencil flowing from the letters are collected into so many several points on the retina. Now, bring the book by degrees so near, that the smallest letters begin to appear confused, and cannot by any straining of the eye be rendered as distinct as they were. Keeping the book at the same distance, look at the letters which are somewhat larger than the former, and the larger letters shall appear distinct. It is manifest from the less distinct appearance of the smaller letters, that at this distance the rays of each pencil are not accurately united in a point of the retina, notwithstanding which the larger letters appear distinct.

If the book be brought still nearer, the smallest print will become quite confused, and the larger will begin to appear indistinct; but, keeping the book at this same nearer distance, a print still larger will appear distinct. In this case, the rays are still less accurately collected into points; and yet the largest letters appear as distinct as the two smaller prints had formerly done.

The experiment may be made the contrary way, by using

a pair of spectacles of a proper convexity; first placing the book at such a distance, that all the sizes of letters appear distinct, and then moving it farther and farther off. The smaller prints will, as before, become confused, one after another, according to their sizes, while the larger still preserve their distinctness.

From these two experiments, it is manifest, that we may have pretty *distinct vision*, when the foci of the pencils are at some distance beyond or before the retina; and that the larger the object, the greater the latitude of aberration, before we are sensible of any indistinctness. So long as the circles of aberration do not coalesce, or overlap each other, the object may be seen without much indistinctness; but whenever they come to touch, and much more when they overlap each other, vision becomes confused.

The *distinct vision* of which we have been speaking, depends on the distance and magnitude of the object jointly; while *perfect vision*, in Jurin's sense of the words, depends only on the distance of the object, and not on its magnitude.

§ 83. *Effects of size in proportion to distance. Contrast of light and shade. Simplicity and complexity of objects. Minimum visibile. Images by inflected light. Objects in motion. Ambient darkness.*

Besides the more or less complete concentration of the rays, emitted by each luminous point of the object, to a focus on the retina, there are various circumstances which influence the distinctness of vision; such as, the size in proportion to the distance of the object, the degree of illumination, the contrast of colours, the simplicity or complexity of the object, its form, and the circumstance of its being in motion or at rest.

Many familiar observations might be mentioned, illustrative of the influence of these particulars; and before proceeding to consider the question of the eye's power of accommodating itself, within certain limits, to the distance of objects, it will greatly aid the student's conception of the subject, if he

previously understands the effects produced by the causes now enumerated.

The effect of size, for example, in proportion to distance, is evident when we regard a house a considerable way off, but which we must approach, before the windows are visible; and nearer still, to discern the bricks and tiles. At a certain distance, we see a white paper on the wall; going nearer, we perceive it is printed; nearer still, we can read the large letters; and at length the smallest letters are legible.

In order to form some estimate, how far distinctness of vision is affected by the size of the object in proportion to its distance, the student may have recourse to some such experiments as the following, described by Harris.[2] In these experiments, the accommodating power of the eye is unrestrained.

Draw upon a card, a parallelogram one inch long and half an inch broad; divide it into squares, the sides of which measure $\frac{1}{10}$ inch, and make each alternate square very black with ink. Having set up the card in ordinary day light, and retreated a good distance from it, the student, advancing slowly, may probably begin to discern some imperfect specks of black and white at the distance of 25 feet$=\frac{3000}{10}$ inch. Hence determining trigonometrically the angle under which each square is seen, it will be found equal to $1' \, 9''$ nearly. The squares will not appear defined and perfect, till within a nearer distance, say 7 feet, when the visual angle will equal $4' \, 5''$.

If the student places, alongside of the first, another card, divided into squares of the same dimensions, with the alternate squares tinged lightly with Indian ink, the squares will not be perceptible at a greater distance than 16 feet; but at the distance of 7 feet, they will appear as well defined as those on the former card.

Let a single black square be drawn on a card, and a single white square on a black ground; also a black round spot, and a parallelogram; and let each be $\frac{1}{10}$ inch in breadth. On another card, repeat the same figures lightly in Indian ink.

The black square, and the white square, will be perceptible as black and white specks, at the distance of 40 feet; but

will not be well defined, till the eye comes to within 7 or 8 feet of them. The square in Indian ink, and white square on a ground shaded with that ink, will not be perceived at a greater distance than 25 feet; but will be well defined at the same distance with the former squares. The black round spot and parallelogram will be perceived at more than 50 feet; but the parallelogram of the same breadth, and the round spot, lightly shaded with Indian ink, will be invisible at the distance of 40 feet.

These experiments show that a simple object, as the black square on a white ground, or the white square on a black ground, can be seen under a less angle than the equal parts of a compound object, such as the squares of the chequered figure; and that their least angle, or *minimum visibile*, in most cases, cannot be less (Harris thinks) than 40″; other observers say 30″. If it is 40″, the size of the image on the retina will be $\frac{1}{8000}$ inch. At a medium, Harris thinks it is not less than 2′. It appears from these experiments, that several contiguous objects are scarcely discernible one from another, unless they each subtend angles that are not less than about 4′. Harris remarks that the difficulty of keeping the eye perfectly steady, may be one cause why a single object can be discerned under a less angle than the parts of a complex one; and that it is natural to suppose, that the fewer the objects we contemplate, and the more they differ in colour, the easier we can distinguish their several impressions on the retina.

On white paper, let the student draw black lines of different lengths, and each $\frac{1}{20}$ inch broad. A line $\frac{1}{4}$ inch long will be just perceptible at the distance of 45 feet; and one of half that length at no greater distance than about 20 feet. Two parallel black lines, each $\frac{1}{20}$ inch broad, with a white line between them, also $\frac{1}{20}$ inch broad, will not appear separate at a greater distance than 20 feet. In like manner, a piece of fine thread or wire is visible at a distance from whence a round spot of the same diameter is totally invisible.

According to Harris, a globular object less than $\frac{1}{650}$ inch in diameter is to the generality of eyes totally invisible; and, except in a few instances, an object cannot be seen that is

less than $\frac{1}{450}$ inch in diameter, an object of this breadth subtending an angle of 1′ at the distance of 8 inches from the eye. But an object, placed on a field differing slightly from it in colour, is not perceptible under a less angle than about 4′, and in such circumstances the smallest visible object is not less than about $\frac{1}{100}$ inch in diameter. At a medium, the breadth of the least globular object that is discernible by the naked eye, is perhaps about $\frac{1}{300}$ inch.

Small wires, threads, or hairs, placed on or before white paper, or suspended in the air in certain situations with respect to the light, are visible under very small angles, such as 2″ or 3″; but in these cases, the light is inflected in passing by the sides of the object, so as to form on the retina images of those sides much wider asunder than the angle which the object subtends at the eye would denote, so that no conclusion can be drawn from such experiments regarding the *minimum visibile*, or diameter of the smallest retinal image which can be perceived.

A small object in motion is more easily discerned than if at rest. Thus, a hair moving in the air, is visible at a greater distance than it could be, if at rest. During the twilight, a small star is sometimes not easily seen through a telescope steadily directed towards it; but on moving the telescope a little, the star becomes distinct. The reason of this seems to be much the same with that of the visibility of a long slender object. By the gradual motion of the image over the retina, the impression upon each part continuing for sometime, the effect is the same as if a linear image were formed.

When the eye is free from extraneous illumination, a very small beam of light falling directly on the retina is sufficient to produce an impression. Thus, in a dark night, the feeble light of a candle is perceptible at a great distance; and the fixed stars, though they have no sensible diameters, are yet very visible.

§ 84. *Nearest and farthest limits of distinct vision. Vision by diverging, parallel, and converging rays.*

When the eye is in a quiescent state, no effort of any kind being used by any of its parts, it is suited to see with perfect vision at some one determinate moderate distance, which, for most eyes, is about 15 or 16 inches. This is sometimes called the *distance of perfect indolent vision*, or the *natural distance* of the eye. When the object is small, such as the letters of a printed book, the distance at which it will be most easily seen is less; perhaps 12 inches. To the generality of eyes, the nearest distance of distinct vision is about 7 or 8 inches. At this distance they commonly read a small print, and examine all sorts of minute objects, such as the divisions of a finely graduated scale. Myopic eyes can see small objects best at the distance of 6, 4, or even 3 inches; and presbyopic eyes at no less distance than 12, 15, or 20 inches; but at present we speak of eyes of natural conformation and youthful vigour.

While the least distance of distinct vision is universally acknowledged to be 7 or 8 inches, considerable diversity of opinion has existed regarding the limitation of its greatest distance. Porterfield states the greatest distance of distinct vision for his own eye to be 27 inches. Jurin calculated that a good eye could accommodate itself to see an object with perfect vision at the distance of 14 feet, 5 inches. Other authors appear to be of opinion that there is no maximum distance to which distinct vision is limited, the eye in its natural state being fitted to bring parallel rays to a focus on the retina; so that when objects at a distance become invisible, they do so only from the smallness of the angle which they subtend at the eye, and from the failure of the light emitted or reflected by them. If this is the case, were the moon's diameter, which subtends at the eye an angle of 30′, divided into 60 equal parts, each of these divisions, subtending an angle of 30″, would be as distinctly seen at the distance of 240,000 miles as the similar divisions of a white disk, 1 inch in diameter, placed at a distance of 115 inches; for the eye discerns

any space, sufficiently illuminated, subtending an angle of 30″.

Although the rays proceeding from objects are never parallel, their divergence, as they emanate from any point of a distant object, is so small, that they are reckoned parallel; and accordingly all optical instruments are adapted in such a manner that the rays, emerging from them, shall be parallel at their incidence on the eye. It is generally said that convergent rays incident on the eye can never be brought to foci on the retina. This is true in ordinary circumstances; but there are instances of the eye being so flat, as to require convex glasses to converge even parallel rays to the retina, which is equivalent to a power of bringing convergent rays to a focus. It is also evident, that an ordinary eye can always see indistinctly by slightly convergent rays, as when it looks through a convex lens at a distant object.

§ 85. *An adjustment to distance generally admitted; but denied by some.*

It is generally admitted that the eye, in its normal state, possesses a power of accommodation, by which it is enabled to produce distinct vision of objects at a great variety of distances. It is supposed to do this, by an increased refraction, so as to shorten its focal length, when near objects are regarded, and by a diminished refraction, so as to lengthen its focal distance, when the object is remote; or by some equivalent change.

There are some authors, however, who deny the necessity for any such power of accommodation.

Magendie, for instance, tells[3] us, that if we take the eye of a white rabbit, which, being destitute of pigment, permits us to perceive on the back of it, through the semi-transparent sclerotica and choroid, the images formed on the retina, these images are distinct, whatever be the distance of the object towards which the cornea is directed. He considers this experiment contradictory to the theory that an accommodating power is necessary, and dismisses very summarily the various

explanations which have been offered respecting the mode in which the supposed change in the eye is effected.

It is probable, that, in this instance, Magendie has been too precipitate in drawing his conclusion. Had he placed two lighted candles at equal distances from the rabbit's eye, and six inches from each other, he would have observed, that, as he withdrew the eye from the candles, the space between the two images on the retina became much more rapidly contracted than the images themselves, so that at no great distance the image of each of the candles equalled or even surpassed that of the space between their two images. This is a consequence of distantial aberration, (§ 81), which, had it happened during the life of the animal, would have produced a false impression of the relative size of the flames to the distance between them, unless the eye possessed an adjusting power, which it probably does, but which of course ceases with life. This simple experiment shows the fallacy of Magendie's views on the subject. He has endeavoured, indeed, to support his notion by the authority of Professor Simonoff, a Russian astronomer, to whose opinion I shall hereafter refer.

§ 86. *De la Hire's doctrine that the sole accommodation consists in the variation of the pupil. Distinctness of vision aided by contraction and dilatation of the pupil. Vision through a perforated card.*

We shall hereafter consider the experiment on which De la Hire[4] founded his fallacious opinion, that the refractive state of the eye is always the same, whether we look at a near or a distant object; and that the whole accommodation to different distances consists in an enlargement and diminution of the pupil.

That a change in the size of the pupil has a considerable effect in rendering objects distinct at different distances, is as undeniable as the fact, that if the eye has been directed to a distant object, and is then turned to one which is near, both being as much as possible equally illuminated, the pupil is observed to contract.

Let P P′, fig. 78, represent the diameter of the pupil, and Q P, Q P′, the extreme rays of a

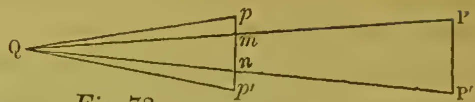

Fig. 78.

pencil diverging from Q, and which the lenses of the eye are capable of collecting to a focus on the retina; then, if the eye approaches Q, and *p p′*, the diameter of the pupil, remains equal to P P′, its former diameter, the extreme rays of the pencil, Q *p*, Q *p′*, which now enter the pupil, diverge more than Q P, Q P′, and therefore cannot be brought to a focus on the retina. But if Q P, Q P′, cut *p p′* in *m* and *n*, and the diameter of the pupil be contracted to *m n*, then the extreme rays Q *m*, Q *n*, coincide with Q P, Q P′; the more diverging rays being cut off, which will aid in rendering the image distinct. It must not be supposed, however, that by Q *m*, Q *n*, coinciding with Q P, Q P′, they will be collected on the same point of the retina as Q P, Q P′ would be. It is an error, not unfrequently adopted, that if the rays which pass into the eye from a distant object and those from a near object have the same divergence, a circumstance which may depend on a mere change in the size of the pupil, they will be collected on the same point of the retina, without any change in the refractive media of the eye. That this cannot be the case, is evident from the fact, that the rays from a distant object and those from a near object, although they may have the same divergence, fall on the cornea at different angles of incidence, and must necessarily meet the axis of the eye at different points, after refraction.

On the principle above explained, namely, that of excluding the lateral rays, we are enabled, by looking through a small hole in a card, to see objects at a less distance than we could with the naked eye. By the same means, the myopic eye is able to discern distant objects, and the presbyopic eye to discern near objects, better than they could do without such a contrivance. In all the three cases, the hole in the card answers the purpose of a farther contraction of the pupil, and excludes those pencils, which, converging either too rapidly or too slowly, would tend towards foci either within or beyond the retina, and thus

form circles of dissipation overlapping one another, instead of coming to focal points.

The magnitude of the circular space on the retina, occupied by the light, proceeding from any given point, depends on two circumstances; viz. the distance between the focus and retina, and the diameter of the pencil of rays emanating from the luminous point; and it is easy to show, that, by lessening either of these, the diameter of the circular spaces over which the light is diffused, may be reduced indefinitely. Therefore, if the light be admitted into the eye through an extremely minute aperture, the circles of dissipation will be proportionally minute, and as the distance of their centres is supposed to remain the same, it is easy to conceive that by making the aperture sufficiently small, they will be prevented not only from overlapping, but even from touching one another.

Let A *b*, A *c*, A *d*, fig. 79, be rays proceeding from the same

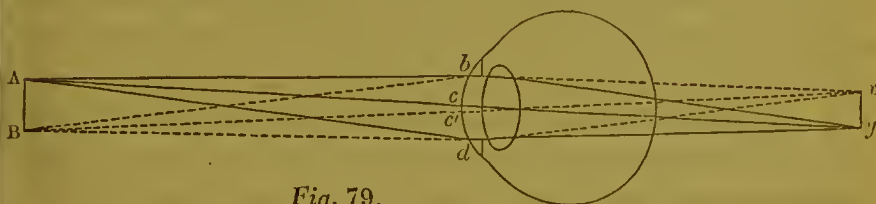

Fig. 79.

point, A, of an object, placed nearer the eye than the distance for distinct vision. These rays would converge towards *y*, behind the eye, and occupy in their course a circular space on the retina. In like manner, the rays, B *b*, B *c′*, B *d*, proceeding from B, would converge towards *x*, and occupy on the retina a circular space partially overlapping that occupied by the rays proceeding from A. It is evident, that if we could interrupt the rays A *b*, A *d*, proceeding from the first point, and the rays B *b*, B *d*, proceeding from the second, a distinct image of the object would be formed on the retina by means of the rays A *c*, B *c′*. This is effected by placing before the cornea, a card perforated with a small opening, so as to allow only the central rays of each pencil to pass.

In a myopic eye, the rays, proceeding from any one point of a distant object, come to a focus within the vitreous humour,

and thence diverging, are diffused over a circular space on the retina. The rays from any other point in the distant object situated very near the former, will also come to a focus within the vitreous humour, will thence diverge, and on reaching the retina will be diffused over a circular space, coinciding more or less with the space occupied by the rays from the first point. A perforated card, placed before a myopic eye, acts as a stop or diaphragm, (§ 62), limits the pencils of rays to those which are the least diverging, and so reduces the circles of dissipation on the retina, that they do not coincide. The consequence is, that the myopic eye discerns distant objects through a pin-hole with considerable distinctness.

The presbyopic eye derives a similar benefit, in looking at near objects, through a perforated card. The only difference is in the rays which are excluded; for, in the myopic eye, they are such as, from over-refraction, would meet at a focus anterior to the retina, while in the presbyopic, they are such as would converge too slowly, and tend to a focus behind the eye.

Were the aperture in the card so small as to transmit merely a single ray from each point of the object, the image would be formed on the retina with absolute precision; but, from the scantiness of the light, the impression, concomitant with the image, would in that case be too feeble for the purposes of vision.

We admit, then, that the contraction of the pupil, when near objects are regarded, assists in rendering vision distinct, by cutting off the extreme rays, and reducing the circle of aberration of each pencil. On the other hand, an enlargement of the pupil gives distinctness to distant objects, by allowing a greater quantity of light to pass into the eye. We even admit that the pupil varies its size, in the adaptation of the eye to different distances, not as a mere concurrent effect, depending on the varying intensity of the light by which the objects are illuminated; but as an action, organically connected with the changes in the refractive parts of the organ, which take place at the same moment.

§ 87. *Inability of the eye to discern near and distant objects, at the same time.*

Numerous proofs are adduced of the necessity of the eye possessing a power of accommodating itself to the different distances of objects.

One of the most obvious is, that, with one eye, the other being shut, we find ourselves unable to see distinctly, at the same time, a near object, and one which is remote, the two being situated nearly in the optic axis.

Of this fact, various illustrations might be mentioned. For example, when we look at one of our fingers, held up at the distance of 7 or 8 inches from one of our eyes, the other eye being shut, the finger appears distinct, and every object beyond it indistinct; but if we look at the remote objects, so as to see them distinctly, the finger becomes indistinct.

Place two lighted tapers at the distance of one inch from one another, and 20 feet from the eye, and place another lighted taper one foot from the eye, so that the images of all the three may fall at once upon the retina. If the eye is directed to the near taper, the flames of the distant tapers become starry, and seem to coalesce; but the instant that the eye is directed to the distant tapers, they appear distinct and separate.

While it is thus true, that we cannot see, at once and distinctly, two objects, remote from another, and placed in the optic axis, De la Hire observes,[5] that it is also true, that we are able to view with much attention but a very small part even of one object, and that the other parts, near that which we are examining, appear to us confused, although they are not sensibly more remote from the eye. He argues, therefore, that we should not be surprised, if we feel a little more difficulty in shifting our attention from a near to a distant object, than we do in seeing another at the same distance; because the light from the two objects, at different distances, strikes the eye differently, and in changing from the one object to the other, it is necessary that the two eye-balls should

change their direction, in order to give to their axes a different angle from what they had at first; for though we are using only one eye, the other does not fail to perform the same movements as if it were open.

These remarks of De la Hire, are not destitute of truth; but they do not, in the slightest degree, disprove the necessity of an accommodating power.

§ 88. *Analogy of the eye to other dioptric instruments.*

Another plain argument is drawn from what is observed in respect to the images of external objects, cast upon a screen, by means of a lens, placed in the window-shutter of a dark room. In order to convert an indistinct image into one that shall be distinct, it is necessary, according to the distance of the object, either to change the lens, for one more or less convex, or to vary the distance between it and the screen. If the lens be of such convexity as to form the image of an object, situated a foot before the lens, distinctly upon the screen, placed 5 or 6 inches behind the lens, the same object, removed to the distance of 6 feet from the lens, will not be represented exactly upon the screen, unless in place of the former lens we substitute one less convex, or diminish the distance between the lens and the screen.

With the portable camera obscura, we slide the lens backward and forward, according to the distance of the object, till we catch the proper focal distance, and find the image clear and distinct.

The conclusion drawn from such facts is, that as the images, formed by other dioptric instruments, are clearest when the pencils are brought to focal points, so it must be in the eye. This cannot be denied; but if it is meant that we see only when the pencils of rays, entering the eye, come exactly to focal points on the retina, the observations of Jurin (§ 82) on the difference between distinct and perfect vision, sufficiently show the fallaciousness of such an opinion.

§ 89. *The presbyopic eye loses the power of accommodation. Fatigue from viewing near objects.*

As we advance in life, not only do the refractive powers of the eye diminish, but we lose the power of accommodating the organ to near objects. The eye, in its state of *perfect indolent vision* is adapted only to distant objects, and it cannot see near objects distinctly, but by an effort. This effort, long persevered in, becomes painful; whereas the regarding of distant objects can be continued without any feeling of fatigue. The power to make the peculiar effort in question is partially or totally lost by the presbyopic eye; a fact analogous to the diminished activity which takes place in all the functions of the body as life advances.

§ 90. *Analogical argument from the vision of diving animals.*

Considering how much less the refraction is, out of water, than out of air, into the eye, it is evident that if the light, emanating from an object, comes to a focus at the retina, the eye being in air, it will converge to points situated considerably behind the retina, if the eye is in water. Hence quadrupeds and birds which dive, could not follow their prey in the water, unless they had a power of altering the disposition of the different parts of the eye, so that, when they plunged, they could bring the rays to meet at the retina. Blumenbach[6] discovered in the Greenland seal, the mechanism by which the accommodation is effected in that animal. Reasoning, then, from analogy, it is probable that an accommodation exists also in the eyes of those animals which require a change of conformation according to the simple proximity or remoteness of objects, although it may perhaps differ in mechanism, and be less considerable in extent, than what exists in diving animals.

§ 91. *Scheiner's experiment. Porterfield and Young's optometer.*

Out of the many optical experiments described by Scheiner, the following is so frequently referred to, that it is known under the appellation of *Scheiner's experiment.*[7]

If two pin-holes, *l*, *m*, fig. 80, be made in a card, at such a

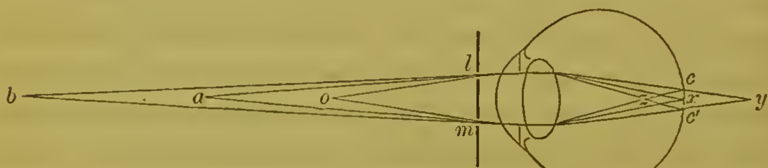

Fig. 80.

distance from each other as to be within the diameter of the pupil, and if the card be held close before one eye, so that a small object can be seen through the holes, the object will appear single at that particular distance at which it would be seen most distinctly by the naked eye, but at any other distance it will generally appear double, even when within the limits of distinct vision. Thus, if *a* be an object at such a distance that its single image, *x*, falls upon the retina, it will appear single; but if it be removed to a greater distance, as at *b*, the focus of the rays proceeding from it will be formed in front of the retina, at *z*, whence, after intersecting each other, they will diverge and form two images, *c*, *c'*, upon the retina. Of these two images that at *c'* will disappear, when the opposite hole, *l*, in the card is closed, and *vice versa*. If the object, again, be too near the eye, as at *o*, a single image of it would be formed at *y*, behind the retina, which in this case receives two images, *c*, *c'*, by means of the rays proceeding from *o*, before they come to a focus. Of these two images, that at *c'* will disappear when the corresponding hole, *m*, in the card, is closed, and *vice versa*.

If the whole space, *l m*, were thrown open, the light from *o*, would be diffused over the whole space *c c'*, and there form one diffused indistinct image of *o;* and the same would be the case with the light flowing from *b*, its focus being at *z*. The

obstacle between the holes, *l*, *m*, cuts off the whole of this light, except what falls at *c* and *c'*. Consequently two separate and distinct points are illuminated, and only two, and therefore two distinct and separate images of the object at *o*, or at *b*, are seen.

De la Hire[8] drew from Scheiner's experiment the conclusion, that the refractive media of the eye underwent no adjustment to distance. His argument ran thus:—It is commonly believed, that an eye, capable of uniting the rays upon the retina, when the object is at *a*, at the distance of perhaps 6 inches, can make such a change in its conformation as still to unite them upon the retina, when the object is removed to *b*, a distance say of 10 inches. Were this opinion true, the eye of the observer, when the object is placed at *b*, would make the supposed change in its conformation. But the experiment shows that the eye is not in such a state as to unite upon the retina the rays proceeding from the object at *b;* for upon bringing the card close before the eye, the appearance is that of two distinct objects, not of one only, as it ought to be, if the eye had undergone the presumed accommodation.

In reply to this argument, Porterfield[9] showed that the intervention of the card interrupts, for the time, the use of the adjusting power; and this for two reasons, viz. *first*, because the mind is unable to judge of the true distance of the object seen through the card, and *secondly*, because the images of the object, placed either at *o*, or at *b*, are, in consequence of the smallness of the holes, formed distinctly on the retina at *c* and *c'*, so that the eye, perceiving the object without confusion, though double, the accommodating power is not called into action, else the object would appear single.

Scheiner's experiment is generally regarded as clearly proving the necessity of an adaptation of the eye for distinct vision at different distances, since it shows that, if no such power is exerted, the image of an object, under certain circumstances, falls in front of the retina, and under others behind it.

Porterfield applied Scheiner's experiment to the determination of the focal distance of the eye; and suggested the con-

struction of an instrument for that purpose, to be called an *optometer*, founded on the principle of the phenomena observed in that experiment. This instrument was improved by Young,[10] so as to afford a simple, convenient, and accurate means of measuring the focal distance of the eye, as well as of proving that we possess a voluntary power of varying the amount of its refractive effects.

If a straight line, three feet in length, is drawn with ink upon a plain white surface, and the eye, placed just above the level of the white surface, is directed along the black line, the latter appears distinct at one point only, while nearer the eye than this point, as well as beyond it, the line appears broad and indistinct. This proves that when the eye is adapted to see distinctly at one distance, it is not adapted to see with equal distinctness at other distances. If the eye is now fixed upon a point in the black line nearer than that which first appeared distinct, but within the limits of distinct vision, this near point becomes clearly defined, while the former and more remote point becomes confused. If a point more distant than the first be regarded, the accommodating power is again exercised, so as to render the more distant point distinct.

Dr Young's optometer is nothing more than such a line, drawn on a slip of card paper, about 8 inches in length, and one in breadth, and an inch of the card turned up at one of its ends, so as to stand at right angles to the rest of its length. Into this perpendicular portion, a thin brass plate is inserted, having two or more narrow slits in it, close enough to be within a space not broader than the pupil. When the line is regarded through these slits, it appears double or triple according to their number, except at the point to which the eye is adjusted. That point appears single, and the apparent lines, produced by the rays proceeding from every other part of the black line forming double images upon the retina, seem to cross each other at the point, the vision of which is distinct. In a sound eye, the crossing of the lines may be made to appear more or less remote by directing the attention successively to different points along the black line, or to other

objects placed at different distances in the optic axis, showing that the eye possesses a voluntary power of adjustment to distances.[11]

§ 92. *Optical necessity of an adjusting power.*

It follows from what has already (§ 82) been said regarding perfect vision and distinct vision, that the eye would in a certain degree possess a power of distinguishing objects, placed at different distances, independently of any internal change; but the question still recurs, Can the *actual* power of distinguishing near and distant objects be reconciled with the supposition that the eye undergoes no change? With the following answer to this question, I have been favoured by Dr Rainy :—

Let $a\,a'$, fig. 81, be the aperture of the pupil, $x\,z$ the axis

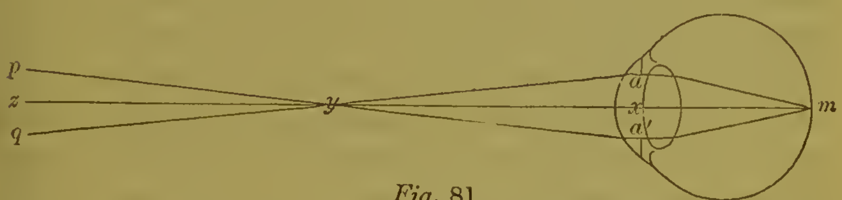

Fig. 81.

of vision, and $x\,y$ the nearest distance of distinct vision. Then, the eye being adapted to view objects at y, a point at y will, by means of the rays $y\,a$, $y\,x$, $y\,a'$, be projected as a point, m, on the retina.

Continue the lines $a'\,y$ and $a\,y$, to p and q, and it is evident, that a ray from p, following the exact course of $y\,a'$, will, if the conformation of the eye remains unchanged, proceed to m. In like manner, a ray from q will follow the course of $y\,a$, and also proceed to m. Therefore, rays from p and q will meet in one and the same point, and consequently p and q will not appear as two separate points, but confused together.

If we take $x\,y = 6$ inches, and $a\,a' = \frac{1}{6}$ inch, then $a\,a'$ will be to $x\,y$ as 1 to 36. Consequently the angle $a\,y\,a'$ will be 1° 35′. Hence two points, $q\,p$, which subtend at y an angle not greater than 1° 35′, would appear confused together. But we know that objects appear distinct, when subtending an

angle of only 1′. Hence the existence of an accommodating power is undeniable.

The same thing may be further illustrated, if from the points *p*, *q*, fig. 82, we draw the lines *p a*, *q a′*, to the margin of the

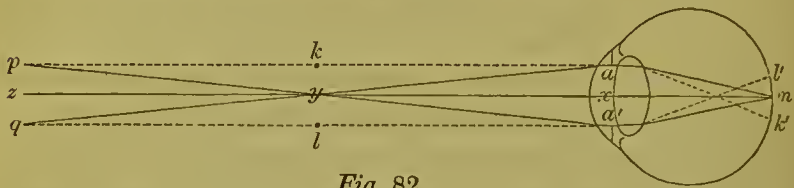

Fig. 82.

pupil, and take the points *k*, *l*, in these lines, at the same distance from the eye as *y*. If the eye brings to a focus rays emanating from points at the distance *x y*, then images of *k* and *l* will be formed at *k′* and *l′*, and will be distinct from one another, and from the image of *y* formed at *m*.

Now, if we take one of the distant points, *q*, the rays issuing from it will, if the eye remains in the same state, be diffused over the space *m l′*; for the ray *q l a′* will proceed to *l′* as the ray *l a′*, from *l*, does, and it was shown above that the ray *q y a* will proceed to *m* as the ray *y a* does; the other rays from *q*, which pass at the different points between *l* and *y*, will proceed to different points between *l′* and *m*, and thus be diffused over a circular area having *l′ m* for its diameter. In like manner, the rays from *p* will be diffused over an area having *k′ m* for its diameter. Therefore, the rays proceeding from *q* and *p* will be diffused over circular areas, touching at *m;* from which it follows, that two objects, at *p* and *q*, would not appear distinct from one another, but confused and in contact, to an eye adapted to view objects at the distance *x y*.

Professor Simonoff[12] assures us, that the circles of aberration from distance, such as *m l′* or *m k′*, are so small, that they cannot interfere with distinct vision. He gives some calculations by which he endeavours to show that they may be considered infinitesimal.

Without entering into a consideration of these calculations, it is plain, that the ray *y a′*, coming from the centre of a near object, will, if the eye remains unchanged, be refracted to the very same point of the retina with the ray *p y a′*, coinciding

with $y\,a'$ in direction and incidence, but emitted from an indefinitely distant object, and from a point in the object not situated in the axis of vision, but at the angular distance $l\,a'\,p$. The question, then, comes to be, whether two very distant objects, or two points in the same object, can be perceived to be quite distinct by the eye when they subtend at the eye the angle $l\,a'\,p$. For in this case it will follow, that however small $l'\,m$ may be, it can be distinctly appreciated in vision.

Now, the angle $l\,a'\,p$ is equal to $a\,y\,x$, $x\,a'$ is equal to the semidiameter of the pupil, and $x\,y$ is the smallest distance at which an object can be easily seen; therefore, $l\,a'\,p$ is equal to an angle having for its radius the least distance at which objects are distinctly visible, and for its arc the semidiameter of the pupil. If the distance $x\,y = 6$ inches, and $x\,a' = \frac{1}{10}$ inch, then the angle $x\,y\,a'$ or $l\,a'\,p$ will be rather less than 1°. It is well known that the eye can distinguish objects of which the angular distance forms only a small fraction of 1°, such as 1′. Therefore, in an eye adapted to see very distant objects, the light coming from the point y of an object placed at the distance $x\,y$ could not be refracted to a point m, but would be diffused over the spaces $m\,k'$ and $m\,l'$, each corresponding to nearly 1° of visible magnitude. But, in fact, the light coming from such a point forms an image which is not diffused over any assignable space. Therefore, the eye which previously brought to a focus rays proceeding from an indefinitely distant object, must, in viewing the near object, have undergone an adjustment.

§ 93. *The eye seeing distinctly at three different distances, the second of which is about double the first, and the third infinite, as great a change necessary for seeing distinctly at the first and second distance, as at the second and third.*

A different conformation of the eye being shown to be necessary for obtaining distinct vision at different distances, it is proper to observe, that, in whatever way the adjustment is effected, if a certain amount of change is sufficient for procuring distinct vision of objects from a moderately small dis-

tance to double that distance, then from that double distance to infinity, another similar amount of change will be all that is required.

Let Q F, fig. 83, be the axis of the eye, A B its semi-aper-

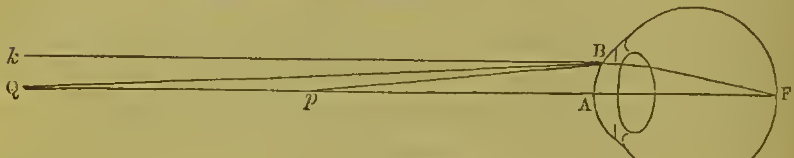

Fig. 83.

ture, p the place of the nearest object that is seen distinctly, Q a second object, so situated that Q p=p B, and let k B be a ray parallel to the axis. Now, because B p=p Q, the angle p B Q=B Q p=k B Q; whence it is sufficiently manifest, that if the eye is so adapted as to unite a ray p B with the axis and the retina at F, as great a change in the eye will be requisite to bring a ray Q B to the retina at F, as will afterwards be necessary to bring the ray k B to the same point.

Hence, as Porterfield[13] observes, if short-sighted persons can read a small print distinctly at two different distances, the longer double the shorter, which most of them can do, it follows that as great changes take place in their eyes, as in perfect eyes that see distinctly at all intermediate distances between infinity and the longer of those two distances. This is the reason why a short-sighted person can see distinctly at all distances, with a single convex lens of proper figure; otherwise he would require different lenses for different distances.

§ 94. *Amount of change necessary to adjust the eye to different distances.*

Various hypotheses have been formed regarding the seat and nature of the change by which the eye, from the state of perfect indolent vision, is adapted to see near objects with distinctness. Some have supposed the axis of the eye to be elongated, others the figure of the cornea or of the crystalline to be changed, and others the crystalline to approach the cornea. We shall presently see that none of these hypotheses

has been proved. Before proeeeding, however, to examine the grounds of each, the question naturally oceurs, What amount of change would be neeessary, to produce such vision at different distances as the eye aetually possesses?

The faeulty of accommodation, as shown by the optometer, exists in very different degrees in different individuals. In general the faeulty diminishes as we advanee in life; while some even of middle age appear to possess it in a very small degree. On this subject, the following facts are stated by Dr Young:—

1. The shortest distance of perfect vision, in his own eye, was 26 tenths of an inch for horizontal, and 29 for vertical rays. This power, he observes, is equivalent to the addition of a lens of 4 inches focus; by which, I presume, he means that if his eye, in the state of relaxation, brought to a focus on the retina rays diverging from an objeet ten inehes distant, and, by an adjusting effort, he could bring to a foeus on the retina rays diverging from an object $\frac{26}{10}$ inch distant, the adjustment was equal to the effect which would be produeed by placing before his eye, in the state of relaxation, a convergent lens of 4 inches focus.

2. Dr Wollaston could see at seven inches, and with rays slightly converging; the difference answering to 6 inehes foeal length.

3. Mr Abernethy had perfeet vision from 3 inches to 30, or a power equal to that of a lens $3\frac{1}{3}$ inches in focus.

4. A young lady of Dr Young's aequaintance could see at 2 inches and at 4; the differenee being equivalent to 4 inches focus.

5. A middle-aged lady could see at 3 and 4 inches; the power of accommodation being only equal to the effect of a lens of 12 inches focus.

Dr Young takes the extent of range of his own eye, as being probably about the medium, and inquires what changes would be necessary, to produce that range; whether the radius of the cornea is supposed to be diminished, or the distanee of the lens from the retina to be increased, or these two

causes to act conjointly, or the figure of the lens itself to undergo an alteration.

1. He calculated that, when the eye is in a state of relaxation, the refraction of the cornea is such as to collect rays diverging from a point ten inches distant, to a focus at the distance of $13\frac{2}{5}$ tenths. This must be on the supposition that the succeeding media, through which the light passes, have the same refractive density as the cornea. (§ 51). In order that the cornea might bring to the same focus rays diverging from a point distant 29 tenths, its radius would require to be diminished from 31 to 25 hundredths, or very nearly in the ratio of 5 to 4.

2. Supposing the change from perfect vision at 10 inches, to perfect vision at 29 tenths, to be effected by a removal of the retina to a greater distance from the lens, this will require an elongation of $\frac{135}{1000}$ths, or more than $\frac{1}{7}$th of the diameter of the eye. In Mr Abernethy's eye, an elongation of $\frac{17}{100}$ths, or more than $\frac{1}{6}$th, would have been necessary.

3. If the radius of the cornea be diminished $\frac{1}{16}$th, or to $\frac{29}{100}$ths, the eye must at the same time be elongated $\frac{97}{1000}$ths, or about $\frac{1}{9}$th of its diameter, in order to be accommodated to such vision as that possessed by Dr Young.

4. Supposing the crystalline to change its form; if it become a sphere, its diameter would be $\frac{28}{100}$ths, and, its anterior surface retaining its situation, the eye would have perfect vision at the distance of an inch and a half. This is more than double the actual change. But it is impossible to determine precisely, how great an alteration of form is necessary, without ascertaining the nature of the curves into which its surfaces may be changed. If it were always a spheroid, more or less oblate, the focal length of each surface would vary inversely as the square of the axis; but, if the surfaces became, from spherical, portions of hyperbolic conoids, or of oblong spheroids, or changed from more obtuse to more acute figures of this kind, the focal length would vary more rapidly. Disregarding the elongation of the axis of the lens, and supposing the curvature of each surface to be changed proportionally,

the radius of the anterior must become about 21, and that of the posterior 15 hundredths.

The amount of the differences in the focal distances for near and distant objects, and the degree of modification required in the eye, had been investigated by Olbers, previously to these observations of Young. Having no opportunity of consulting the work of Olbers, *De Internis Oculi Mutationibus*, I must content myself with borrowing the results of his investigations from Professor Müller.[14]

The distance of the image from the cornea, when the objects were at the distance of 4, 8, and 27 inches, and at infinite distance, was found by Olbers to be respectively as follows:—

Distance of the object.	Distance of the image from the cornea.
Infinite, . . .	.8997 Paris inch.
27 inches, . . .	.9189 " "
8 " . . .	.9671 " "
4 " . . .	1.0426 " "

So that the difference between the focal distances of the image of an object at such a distance that the rays are parallel, and of one at the distance of 4 inches, is only .143 Paris inch, or .152 English. According to this calculation, the change in the distance of the retina from the lens, required for vision at all distances, supposing the cornea and lens to suffer no change of form, would be very nearly $1\frac{1}{2}$ line, which might be effected either by an elongation of the eye, or by a change in the position of the lens.

As the same object might be attained, without any alteration in the distance of the lens from the retina, by a change in the convexity of the cornea, Olbers also calculated the amount of change in the convexity of the cornea which would be required for distinct vision at different distances. The radius of the convexity of the cornea for vision at different distances, would be as follows :—

Distance of the object.	Radius of the cornea.
Infinite, . . .	.333 Paris inch.
27 inches, . . .	.321 "
20 " . . .	.303 "
5 " . . .	.273 "

If the radius of the cornea were capable of modification between .333 and .300 inch, and the axis of the eye capable of being lengthened ½ line, distinct vision at all distances beyond 4 inches would be provided for.

The same thing could be attained by a change in the curvatures of the crystalline, but on this part of the inquiry Olbers does not appear to have entered.

§ 95. *Hypotheses formed to account for adjustment.*

The most probable hypotheses, regarding the manner in which the eye is adjusted to the vision of near objects, are the following:—

1. An elongation of the axis, so that the distance between the cornea and retina is augmented.
2. A shortening of the radius of curvature of the cornea, so that its convexity is increased.
3. A change in the figure of the crystalline, so that its surfaces become more convex.
4. A movement of the crystalline towards the cornea.

Some authors suppose the whole adjustment to depend on one only of these changes; others admit that several of them are likely to take place together. Different agents are also presumed, by different physiologists, to produce the same change. An elongation of the axis, for example, has been attributed by some to the action of the straight muscles, and by others to that of the oblique muscles of the eye. In like manner, a change in the figure of the crystalline has been ascribed by some to an action of the capsule which contains the lens, and by others to an action of the fibres of the lens itself. To give a minute account of all the notions, which have been entertained, regarding the changes by which it has been supposed that the adjustment could be produced, would far exceed our limits; much more to explain fully the mechanism by which it has been thought that such changes could be effected, and the controversial views which have been advanced on the subject.

§ 96. *Adjustment supposed to be effected by the external muscles of the eye.*

It has been supposed, that the retina might be removed to a greater distance from the cornea, and also the refractive effect of the media might be increased, by a contraction of the straight muscles of the eye, of the oblique muscles, or of both these sets of muscles together.

The four straight muscles take their origin from the depth of the orbit, and, advancing over the ball of the eye, are inserted, by flat thin tendons, into the sclerotica, about two lines from the edge of the cornea. Those physiologists, who regard these muscles as the chief agents in adjusting the eye to the vision of near objects, tell us, that the four recti, when they contract, must necessarily compress the sides of the eyeball, and thus elongate its axis, so as to increase the distance between the retina and the cornea; forcing at the same time the aqueous humour forward against the centre of the cornea, and augmenting the convexity of the latter. This change of curvature will add to the refractive power of the cornea, or, in other words, shorten its focal length; while, in the elongation of the axis of the eye, the vitreous, crystalline, and aqueous humours will also be lengthened, and consequently the focal length of the eye shortened, so that the rays diverging from a near object may be brought to focal points on the retina. That the eyeball is not made to recede in the orbit by the action of the recti, is sufficiently proved by its not having done so in the experiments of Mr Ramsden and Sir Everard Home, hereafter to be noticed.

The inferior oblique muscle arises from the anterior-internal part of the floor of the orbit, and is inserted into the posterior-external part of the sclerotica, about two lines from the entrance of the optic nerve into the eye. The superior oblique arises deep in the orbit, its tendon passes through a pulley at the superior-internal part of the front of that cavity, whence, changing its direction, it passes to the posterior-external part of the sclerotica, where it is inserted, three or four

lines from the entrance of the optic nerve. The two obliqui thus embrace, by their broad flat tendons, the temporal half of the eyeball. Those physiologists who consider these muscles as the means by which the eye is adjusted to near objects, are of opinion, that, by their contraction, the vitreous humour is compressed, so that the retina is moved backward, and the crystalline forward. They tell us,[15] that the structure of the vitreous humour is peculiarly adapted to the function of accommodation, in so much as it consists of cells filled with fluid, in front of which rests the lens as on a soft elastic cushion; that the vitreous body and the lens easily yield to the pressure of the obliqui, and that when these muscles become relaxed, the vitreous cells instantly resume their former shape, and allow the lens to spring back again towards the retina. They urge, also, the consentaneous convergence of the two optic axes, and contraction of the pupils, which take place when we look at a near object; viewing the former of these motions as an action of the obliqui, and the latter as owing to the stimulus communicated to the iris through the short root of the lenticular ganglion, which is derived from the branch of the motor oculi going to the inferior oblique.

That the eye is easily compressible, and that the effects produced by mechanical pressure correspond with those which might probably arise from contraction of the straight muscles, Dr Hossack has endeavoured[16] to show by experiment. With a speculum oculi, I presume a ring-shaped one, he made a very moderate degree of pressure on his eye, while directing his attention to an object at the distance of about 20 yards. He saw it distinctly, as also the different intermediate objects; but endeavouring to look beyond it, every thing appeared confused. He then increased the pressure considerably, in consequence of which he was enabled to see objects distinctly, much nearer than the natural focal distance. For example, holding before his eye, at the distance of about two inches, a printed book, he could distinguish neither the lines nor the letters; but on making pressure with the speculum, he distinguished both with ease. The cause must have been an inflection of the cornea.

§ 97. *Ramsden and Home attempt to measure the presumed change in the curvature of the cornea.*

It was the opinion of Mr Ramsden,[17] that the principal use of the crystalline was to correct the spherical aberration of the cornea. He was confirmed in this opinion, by some experiments which he made on a man, from one of whose eyes the lens had been extracted, on account of cataract. The experiments appeared to show that the power of the eye, by which it is adjusted to distances, does not reside in the crystalline. It occurred to him, that if the curve of the cornea was susceptible of undergoing any change, this would vary the refraction of the rays, so as considerably to alter the focus of the eye; and from calculation, it appeared that a very small alteration in the cornea would vary the adjustment of the eye from parallel rays to its shortest distance of distinct vision.

From these considerations, Mr Ramsden and Sir Everard Home were led to inquire how far the curvature of the cornea might be subject to change. They found by trial that this part of the eye possesses such a degree of elasticity, that when stretched so as to be elongated $\frac{1}{11}$th of its diameter, it immediately contracts to its former length, upon being left to itself.

It remained to be determined by experiment, on the living subject, whether the curvature of the cornea varies, as the eye adapts itself to different distances. For this purpose, Mr Ramsden provided an apparatus, consisting of a thick board steadily fixed, in which was a square hole, large enough to admit a person's face; the forehead and chin resting against the upper and lower bars, and the cheek against either of the sides; so that, when the face was protruded, the head was steadily fixed; and in this position one of the eyes projected beyond the outer surface of the board. A microscope, properly mounted, so as with ease to be set in every requisite position, was applied to view the cornea with a magnifying power of 30 times. In this situation, the person whose eye was the subject of experiment, was desired to look at the corner of a chimney in a neighbouring street, distant 235 yards,

through a small hole in a brass plate, fixed for that purpose, and afterwards to look at the edge of the hole itself, which was only six inches distant. After some management and caution, which the delicate nature of the experiments required, the motion of the cornea became distinct. The circular section of its surface remained in a line with the wire in the field of the microscope, when the eye was adjusted to the distant object, but projected considerably beyond it when adapted to the near one. When the distant object was only 90 feet from the observer, and the near object six inches, the difference in the prominence of the cornea equalled $\frac{1}{800}$ inch. These experiments were repeated, and varied, at different times, and on different subjects. The observer at the microscope found no difficulty in determining, from the appearance of the cornea alone, whether the eye was fixed on the remote or the near object.

From these experiments, Mr Ramsden and Sir E. Home concluded, that in changing the focus of the eye, from seeing with parallel rays to vision at a near distance, there is a visible alteration produced in the figure of the cornea, by which it is rendered more convex: and, that when the eye is again adapted to parallel rays, the alteration by which the cornea is brought back to its former state is equally visible.

In animal bodies, there are many instances of elasticity being substituted for muscular action; so that if a state of the cornea fitting it for parallel rays were the effect of elasticity, while a change accommodating it to near distances were produced by muscular action, the fact would be quite analogous to what happens in the performance of other functions.

Another method suggested itself of putting to the test of experiment the theory of adjustment, depending on a change in the radius of the cornea; namely, that if the convexity of the cornea became increased to a certain extent, when the eye was directed to a near object, the change might be estimated by an image, reflected from the surface of the cornea, and viewed in an achromatic microscope, supplied with a divided eyeglass micrometer.[18] From the difficulty of steadying the head and eye, the time lost in bringing the cornea into the

focus, and the smallness of the object, this mode of observation afforded no satisfactory result. Mr. Ramsden and Sir E. Home concluded, however, that the change in the curvature of the cornea could not be more than $\frac{1}{125}$ inch, as any greater quantity would probably have been distinctly seen. This amount of diminution of the radius is more than equivalent to the result of their former experiments, which gave only $\frac{1}{800}$ inch as the increased prominence of the cornea. "This change in the cornea," says Sir Everard, "on the first view of the subject, appeared sufficient to account for the adjustment of the eye, and when the lens is removed it probably may be sufficient; but the refractions at the cornea are so much changed by those at the lens, as considerably to lessen their effect in fitting the eye for seeing near objects, and make this small increase of convexity inadequate to such an effect."

The general conclusion which Mr Ramsden and Sir E. Home drew from their investigations was, that the adjustment is produced by three different changes in the eye, viz. an increase of curvature in the cornea, an elongation of the axis, and a motion of the crystalline. These changes they regarded as depending in a great measure upon the contraction of the four straight muscles. Mr Ramsden computed that the increase of curvature of the cornea was capable of producing one-third of the effect, and the change of place of the lens and elongation of the axis the other two-thirds of the quantity of the adjustment necessary.

§ 98. *Olbers and Young perceive no variation in the image reflected from the cornea, when the eye is adjusted to different distances.*

It would appear that Olbers had been unsuccessful in his attempts to measure the presumed change of the cornea, at the same time that his opinion was in favour of its existence.[19]

Dr Young[20] repeated, in various ways, the examination of the image reflected from the cornea, but he could not perceive the least variation in the image, on adjusting the eye from one distance to another.

He thinks that the sufficiency of the methods which he employed, is proved by the following experiment. Make pressure along the edge of the upper eyelid with a pencil, or any small cylinder, and the optometer, with its plane held first horizontally and then vertically, shows that the focus of horizontal rays is a little elongated, while that of the vertical rays is shortened; an effect which can be owing only to a change of curvature in the cornea. Even the unassisted eye of the observer is capable, in this instance, of discovering a considerable change in the image reflected from the cornea, although the change be much smaller than that which is requisite for the accommodation of the eye to different distances. On the whole, Dr Young concludes, that if the radius of the cornea were diminished but $\frac{1}{20}$th, the change in the reflected image would be very perceptible. The whole alteration of the eye requires one-fifth. At the same time, it is worthy of remark, that only one of Dr Young's attempts to detect a variation in the image reflected from the cornea, according to the distance to which the eye was adjusted, was made on another person; the rest were made on himself, and without any magnifying power. Notwithstanding the dependence which he placed on his naked eye, in measuring small distances, and his belief that he had acquired such a command over the power of accommodation, as to be able to view an object without adjusting his eye to its distance, it is not likely that his naked eye could have detected such changes as Mr Ramsden found inappreciable with the aid of the microscope, or that he could minutely examine in a mirror the image reflected from his cornea, except with the eye adjusted to the vision of near objects.

§ 99. *Young finds the adjusting power to continue, although the refraction of the cornea is interrupted.*

Dr Young had recourse to another kind of experiment, which he considered decisive against the hypothesis of the cornea being the organ of adjustment. To understand this experiment, it is necessary to know, that Dr Young's eye, in a

state of relaxation, collected, to a focus on the retina, rays diverging vertically from an object at the distance of ten inches from the cornea, and rays diverging horizontally from an object at seven inches distance. (§ 49.) The cause of the diversity, he considered to be an obliquity of the iris and crystalline to the optic axis.

He took a double-convex lens, of $\frac{8}{10}$ inch focal length, fixed in a socket $\frac{1}{5}$ inch in depth, and, securing its edges with wax, he dropped into the socket a little water, nearly cold, till it was three-fourths full, and applied it to his eye, so that the cornea entered half-way into it, and was everywhere in contact with the water. His eye immediately became presbyopic, and the refractive power of the lens, used in the experiment, being reduced by the water to a focal length of about $\frac{16}{10}$ths, was not sufficient to supply the place of the cornea, rendered inefficacious by the intervention of the water; but the addition of another lens, of $5\frac{1}{2}$ inches focus, restored the eye to its natural state, and somewhat more. He then applied the optometer, and found the same inequality in the horizontal and vertical refractions as without the water. In both directions, the eye had a power of accommodation equivalent to a focal length of four inches, as before, (§ 94); and, it is evident, that this power must have been independent of any change in the cornea.

§ 100. *Proofs adduced by Young that no elongation of the axis takes place, in adjusting the eye to a near object.*

Having satisfied himself that the cornea is not concerned in the accommodation of the eye, Dr Young next turned his attention to the inquiry, whether any alteration in the length of the axis could be discovered. Considering that such a change, if it constituted the whole accommodation, would amount to one-seventh of the diameter of the eye, (§ 94), he flattered himself with the expectation of submitting it to measurement.

Were the axis elongated one-seventh, the transverse diameter of the eye would be diminished one-fourteenth, and the

semidiameter would be shortened $\frac{1}{30}$ inch. He, therefore, placed two candles in such a way, that, when the eye was turned inward, and directed towards its own image in a mirror, the image of one of the candles appeared upon the external margin of the sclerotica, so as to define it distinctly by a bright line, while the image of the other candle was seen in the centre of the cornea. No visible diminution in the distance of the two images took place, when the focal length of the eye was changed.

Dr Young next tried an experiment, in which he rendered an elongation of the axis impracticable. With the eye turned as much as possible inward, and confined by a strong oval iron ring, pressed against it at the internal angle, he applied the ring of a key at the external angle, forcing it in as far as the sensibility of the integuments would admit, and wedging it between the eye and the bone. In this situation, the spectrum, caused by the pressure, extended within the field of perfect vision, and was very accurately defined. Supposing the distance between the key and the iron-ring invariable, the elongation of the eye must have been totally or very nearly prevented; and, on adjusting the eye to a near object, instead of an increase of the eye's axis, the oval spectrum, caused by the pressure, would have spread over a space at least ten times as large as the most sensible part of the retina. But no such circumstance took place; the power of accommodation was as extensive as ever, and there was no perceptible change, either in the size or in the figure of the spectrum.

Dr Young observes, that even if there were no difficulty in supposing the muscles to elongate the eye in every position, yet at least some small difference would be expected in the extent of the change, when the eye is in different situations, at an interval of more than a right angle from each other. The optometer shows that there is none; the adjusting power is the same in whatever direction the eye is turned.

§ 101. *Adjusting power lost by extracting the crystalline.*

Many philosophers have referred the adjusting power of

the eye to the crystalline. Before entering on the question, whether a change of place in the lens, or a change of figure, is the more probable supposition, it is natural to inquire, if the adjusting power continues, after the lens is extracted from the eye.

It is well known, that to an eye deprived of the crystalline, the same glass is not equally useful for seeing all objects distinctly, but that one of about $2\frac{1}{2}$ inches focus is necessary for seeing near objects, and one of about $4\frac{1}{2}$ for seeing distant objects. This affords a strong presumption that such an eye has lost the power of accommodation.

Porterfield suggested[21] the experiment to be made in the following manner:—Cover that side of the glass which is to be next the eye, with black paper, in the middle of which let there be two narrow parallel slits, whose distance from one another does not exceed the diameter of the pupil. If the eye retains its power of accommodation, a small object, at such a distance as to appear single through the slits, when the other eye is shut, will, on opening both eyes, and directing them to a more remote object, appear double. If no such double appearance can be seen, we may conclude with certainty, that the eye has lost its adjusting power. The same thing may be ascertained by employing the optometer.

The experiments of Mr Ramsden, to which reference has already (§ 97) been made, and from which he was led to believe that the power of adjustment was preserved, although the crystalline was absent, were not performed in the manner directed by Porterfield, but simply by placing before the eye a convex lens, and noticing the distance at which the patient saw the letters of a printed book. They appeared most distinct at $4\frac{1}{2}$ inches, and the extreme distances at which they could be read were $2\frac{1}{2}$ and $5\frac{1}{2}$ inches. Dr Young remarks,[22] that the distinction made by Jurin, (§ 82), between distinct vision and perfect vision, explains away the whole evidence adduced by Mr Ramsden.

On trying with the optometer a number of eyes, whence the crystalline had been extracted, Dr Young found, that, though letters could be distinguished at different distances,

the point of intersection of the lines on the optometer, though at different distances from the eye in different individuals, was in each individual invariably at the same distance, or, in other words, the actual focal distance was unchangeable. The conclusion is, that those persons who are deprived of the crystalline are unable to change the refractive state of the eye; and, therefore, that the organ of adjustment, in the natural state, is the crystalline.

§ 102. *Young's proofs of a change of figure of the crystalline.*

Dr Young states two experiments, which he considers, in the *first* place, to come very near to a mathematical demonstration of the existence of an internal change of the figure of the crystalline, and, in the *second*, to explain in a great measure the origin of the change, and the manner in which it is effected.

He describes the appearances of the imperfect image of a minute lucid point, such as the reflection of a candle from a small concave speculum, at different distances from his eye, in a state of relaxation. If the point was beyond the farthest focal distance of the eye, it assumed a starry appearance, the central part being considerably the brightest. When the focal distance of the eye was shortened, the imperfect image was of course enlarged; and, besides this necessary consequence, the light was also very differently distributed, the central part becoming faint, and the margin strongly illuminated, so as to have almost the appearance of an oval ring. If he applied the upright part of the optometer, the shadows of the opaque strips intervening between the slits, while the eye was relaxed, were perfectly straight, dividing the oval into parallel segments, and that whether the slits were held vertically or horizontally; but, when the accommodation took place, the shadows immediately became curved, and the more so the further they were from the centre of the image, to which their concavity was directed.

The same appearances were equally observable, when the

effect of the cornea was removed by immersion in water, so that neither the form nor relative situation of the cornea was concerned in the effect. On the supposition that the refraction of the lens remained the same, no change in the distance of the retina could produce a curvature in the shadows, which in the relaxed state of the eye, were found to be in all parts straight. Dr Young concludes, therefore, that the only imaginable way of accounting for this diversity, was to suppose, that, when he exercised the adjusting power, the central parts of the lens acquired a greater degree of curvature than the marginal parts.

He found this explanation confirmed by the optometer; for, when he looked through four narrow slits, without exertion, the lines always appeared to meet in one point; but, when he made the intersection approach him, the two outer lines met considerably beyond the inner ones, and the two lines of the same side crossed each other at a still greater distance.

Such an aberration as Dr Young describes in these experiments, will be met with only in eyes of peculiar conformation. One case, however, he considered sufficient to establish his argument. Pursuing the investigation by means of the optometer, he thought he had obtained data, from which to determine pretty nearly, into what form the lens must be changed, supposing both its surfaces to undergo proportional alterations of curvature. He concluded, that the elongation of its axis would not exceed $\frac{1}{50}$ inch; and that the protrusion would be chiefly at the posterior vertex. He believed the change to be effected, without any diminution of the transverse diameter of the lens; the anterior surface assuming the form of a portion of a hyperboloid, and the posterior becoming parabolical.

§ 103. *Alleged muscularity of the crystalline.*

It seems unnecessary to dilate on the notion of Leeuwenhoek,[23] that the crystalline capsule might possibly be muscular, and capable of altering the figure of the lens, as the purposes of vision required. Not that the notion is absurd.

On the contrary, it appears fully as likely to be just as the opinion supported by Pemberton,[24] John Hunter,[25] Young, and others, that the fibres of the lens are muscular, and by their contraction produce such a change of figure as is above described. It is plain, that if the crystalline alters its figure, in the manner supposed by Dr Young, the capsule, by which it is closely embraced, must undergo a similar change of figure.

The fibres of the crystalline are prismatic in form, and brittle in consistence, totally differing in these respects from muscular fibres. Berzelius[26] believes the lens to be soluble in water, and argues from this circumstance, that it cannot possess the properties of a muscle. The fact is, however, that on maceration in water, the fibres do not dissolve, but only break down into small particles, easily recognised under the microscope. When the water in which the crystalline has been digested is exposed to heat, the coagulum which forms appears as if albuminous. The crystalline is probably a peculiar animal substance.

Muscular fibres contract during life, only when stimulated to do so through the nerves. Dr Young laboured to trace nerves into the lens, and sometimes he imagined he had succeeded. He states his full conviction of their existence, and of the precipitancy of those who have absolutely denied it. He remarks, with correctness, that the quantity of the ciliary nerves which proceeds to the iris, appears to be considerably smaller than that which arrives at the place of division, which is in the annulus gangliformis of the choroid. Hence, he concludes, that there can be little doubt that the division is calculated to supply the lens with some minute branches. The ciliary processes are more likely, I think, to be the destination of those branches which do not go to the iris.

Mr Hunter suggested an experiment, for ascertaining how far a contraction in the lens might be excited by art, and observed after death. He said that the crystalline, taken from an animal recently killed, might be considered as still alive. Having found that a certain degree of heat, applied through the medium of water, will excite muscular action, after almost every other stimulus has failed, he proposed to

apply this to the lens, and ascertain its effects. The lens was to be immersed in water of different temperatures, and placed in such a manner as to form an image of a luminous well-defined object, by a proper apparatus for that purpose, so that any change of that image, from the stimulating effects of the warm water upon the lens, would be ascertained. Soon after Mr Hunter's death, Dr Young pursued the experiment thus suggested; but obtained no satisfactory evidence of a change in the lens, not even when it was submitted to the influence of electricity.

The hypothesis, then, that the accommodation of the eye to near objects consists in an increased convexity of the lens, produced by a muscular motion of its fibres, must be regarded as totally unsupported by proof. Even taking it for granted that the fibres were muscular, it is by no means clear, that, arranged in the way they are, their contraction would produce the effect of increasing the convexity of the lens.

§ 104. *Adjustment to near objects supposed to be effected by a motion of the crystalline towards the cornea. Anatomy of the parts at the base of the iris, and surrounding the crystalline. Brewster's experiment on adjustment. Travers's hypothesis. Antagonism of the pupil and ciliary circle. The author's hypothesis.*

A motion of the crystalline towards the cornea has often been supposed to be, partly or entirely, the means by which the adjustment of the eye to near objects is effected. The late Dr Monro[27], for instance, believed that the oblique muscles, by their pressure on the eye, increased the distance of the lens from the retina; while it was the opinion of Porterfield,[28] that the lens was drawn forward by the action of the ciliary processes, which he maintained to be muscular.

It has already (§ 2) been stated, that the portion of the choroid coat which is in contact with the vitreous humour, receives the name of the *corpus ciliare*, or *ciliary ring*, and terminates around the crystalline body in about seventy plaits or folds (6, fig. 3.) called the *ciliary processes*. While the

inner surface of the choroid forms the ciliary ring, its outer surface presents the *annulus albidus*, or *annulus gangliformis*, the anterior edge of which, by an adhesion to the internal surface of the sclerotica, constitutes the *ciliary ligament*. The annulus albidus receives the ciliary nerves, as they advance between the sclerotica and the choroid; and from it they pass to the iris, and probably to the ciliary processes. The iris is attached by its great circumference to the anterior part of the annulus albidus.

Returning to the inner surface of the choroid, we find that the ciliary ring corresponds to a somewhat similar ring of the hyaloid membrane, called the *zonula ciliaris*, which is also plaited or folded, so that its processes are received between those of the ciliary ring. Both the ciliary ring of the choroid, and the zonula ciliaris of the hyaloid, are very vascular. Beneath the zonula, is a canal, formed in the hyaloid membrane, and surrounding the crystalline body, known by the name of the *Petitian canal*.

No muscular fibres have been detected in the ciliary ring, nor in the zonula ciliaris, any more than in the iris. A corona of filaments extends from the posterior surface of the ciliary processes to the crystalline capsule, forming the *orbiculus capsulo-ciliaris*. These filaments are fine like spider's web, and very elastic. The terminations of the ciliary processes project into the posterior chamber, but do not adhere to the crystalline capsule. The notion, therefore, that, by a muscular contraction, they can draw the crystalline body forward is untenable. If the lens, by any other means, is moved forward, the filaments of the orbiculus capsulo-ciliaris may, by their elasticity, assist in carrying it back, when the adjustment to near objects is discontinued.

This short anatomical description shows how complicated the parts are, which are situated at the great circumference of the iris and immediately around the crystalline, and which are in all probability occupied more or less directly in the function of adjustment. Were the crystalline an immoveable, unalterable part, embraced simply by an opaque ring, also destitute of the power of motion or of change, it is not likely that

the ciliary body and neighbouring parts would be elaborated in the way they are. That the ciliary processes, zonula ciliaris, Petitian canal, and orbiculus capsulo-ciliaris have all their several uses, cannot admit of a doubt; and that their functions are subsidiary to those of the crystalline is extremely probable, although as yet we possess very little positive knowledge on the subject.

When the pupil is dilated by belladonna, the eye loses its power of seeing near objects distinctly. This fact has generally been regarded as consistent with every theory of adjustment, but a more correct view of the matter was deduced by Sir David Brewster[29] from the following experiment. He took a piece of paper, as shown in the annexed figure, and wrote upon it the three words, ON THE EYE.

ON	THE	EYE

Having placed a fold of white paper behind the word THE, and two folds behind the word EYE, he fixed the piece of paper at one end of a square draw-tube, and placed his eye at the other end, so that he could read all the words by the transmitted light of a candle held behind the paper. The word ON was most luminous; the word THE was less luminous, and the word EYE still less so. He now brought the paper as near his eye as he could without interfering with the perfect distinctness of the word ON. When this was done, no exertion whatever could enable him to read the word THE, and still less the word EYE. He then looked at them through a small aperture, which, upon De la Hire's principle, ought to have given him distinct vision, but it produced the opposite effect, and increased the indistinctness of the last two words. But by making the words THE and EYE as luminous as the word ON, or by bringing another candle near the eye, so as to force the pupil to contract still farther, they could be read with facility.

From this experiment Sir David Brewster draws the three following inferences.

1st. That the contraction of the pupil which accompanies the adjustment of the eye to near objects does not produce distinct vision, by the diminution of the aperture, but by some other action which accompanies it.

2d. That the eye adjusts itself to near objects by two actions, one of which is *voluntary*, depending wholly on the will, and the other *involuntary*, depending on the stimulus of light.

3d. That when the voluntary power of adjustment fails, the adjustment may still be effected by the involuntary stimulus of light.

That the power of adjusting the eye depends on the mechanism which contracts and dilates the pupil, appears to Sir David a conclusion which it is impossible to avoid; and, since the adjustment is independent of the variation of its aperture, it must be effected by the parts which are in immediate contact with the basis of the iris. He remarks, that, though we may never be able to point out the precise manner in which the action excited at the base of the iris produces the adjustment; yet, by excluding all other possible hypotheses, it may not be difficult to fix upon the true one, and establish it by that degree of evidence which is deemed satisfactory in other physiological inquiries.

The mechanism at the base of the iris may be conceived to produce the adjustment in four ways. 1st. By elongating the eye during the contraction of the pupil. 2d. By increasing the convexity of the cornea. 3d. By altering the convexity of the capsule of the lens. 4th. By increasing the distance of the crystalline lens from the retina. The first two of these modes of adjustment Sir David regards as excluded by the observations of Mr Ramsden and Sir E. Home. The third mode, he conceives, cannot produce the effect, because the *liquor Morgagni*, in which, he says, the lens floats, has nearly the same refractive power as the aqueous humour, and therefore no change in the curvature of a membrane which separates them, could produce a perceptible deviation in the transmitted rays. He assumes, therefore, the last hypothesis as the only probable one, namely, the removal of the lens from the retina, when the pupil contracts.

Whatever judgment Sir David Brewster may have formed of the observations of Mr Ramsden and Sir Everard Home, it is evident,[30] that by these experimenters themselves, they

were not regarded as excluding, but as confirming, the hypothesis of an increase of curvature in the cornea, and an elongation of the axis of the eye, along with a motion of the crystalline. At the same time, it must be confessed, that there is no likelihood of the mechanism at the base of the iris being employed in producing either of these changes. Sir David's objection to the third hypothesis which he enumerates, falls entirely to the ground, when we consider that during life, and even for sometime after death, the crystalline is firmly adherent to the capsule in which it is contained, and that the liquor Morgagni accumulates between the two only as an effect of decomposition. The refractive index of the anterior wall of the crystalline capsule has not been determined, but is probably considerably greater than that of the aqueous humour; and as it embraces closely the exterior part of the crystalline, whose index Sir David Brewster estimates at 1.3767, it cannot be a matter of doubt that a change in the curvature of the capsule would materially affect the refraction produced by the crystalline. Whether there are powers in the living eye sufficient to change the curvature of the capsule is another question.

In our present state of knowledge, it matters little whether we hold to the hypothesis of the muscularity or to that of the non-muscularity of the ciliary processes. A much more important question is, whether the ciliary ring is always found in the same state in the dead eye, and in the same relative position to the crystalline.

Mr Travers[31] is of opinion, that the pupil, and the ciliary circle, or termination of the ciliary processes around the crystalline, contract together and expand together. He thinks, that by the contracted state of the pupil, the ciliary processes will be closed and braced together, and bearing upon the circumference of the crystalline, will elongate its axis.

In a short paper which I published[32] on this subject in 1834, I stated, that we had little more than one fact, established by observation, regarding the question of adjustment; viz. the contraction of the pupil when near objects are viewed, and its expansion when the eye was directed to objects at a

distance, as was readily ascertained by inspecting the healthy eye in any living individual, but that I had observed, in the dead eye, another fact, which seemed to bear upon the question.

After death, the pupil generally presents a medium size, but in some eyes we find it small, and in others large. In those eyes in which we find the pupil small or contracted, we find the ciliary circle expanded, so as to be separated a considerable way from the lens; but in those eyes in which the pupil is large or dilated, we find the ciliary circle contracted round the edge of the lens, or even intruding on the anterior surface of the capsule.

Soemmerring, in his magnified section of the eye,[33] has represented the ciliary circle as I find it when the pupil is contracted after death; and Sir E. Home has represented[34] it as I find it when the pupil is expanded; or rather he has exaggerated the contraction of the ciliary circle, and brought the processes more in front of the crystalline than they are ever seen to be. But the facts, as I have stated them from preparations of the eye now before me, derive additional confirmation from the apparently contradictory representations of those two anatomists.

The hypothesis, then, which I have formed, is, that the pupil and the ciliary ring are antagonists; so that, while the pupil contracts, on our directing our attention to near objects, the ciliary circle expands, and when we look at distant objects, the pupil expands, and the ciliary circle contracts around the lens. If it be asked, what purpose could be served by such a motion of the ciliary circle, the answer must be merely hypothetical, and amounts to a conjecture, that as the ciliary circle expands, the crystalline is allowed to advance towards the pupil, but that by its contraction, the crystalline is made to retire towards the retina. These changes of place may be accompanied by a change of figure of the crystalline, its axis becoming elongated in the first case, and shortened in the second. Nor is it at all improbable, that the contraction of the straight and oblique muscles, while it tends both to elongate the axis of the eye and shorten the radius of curvature of the cornea, aids the advance of the crystalline.

Sir David Brewster observes, that "there is no part of the physiology of the eye which has excited more discussion than the power by which it accommodates itself to different distances." I fear we must also join with him in the following remark :—" Although the most distinguished philosophers have contributed their optical skill, and the most acute anatomists their anatomical knowledge, yet, notwithstanding all their combination of science, the subject is as little understood at the present moment as it was in the days of Kepler, who first attempted the solution of the problem."

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[1] Essay upon Distinct and Indistinct Vision, at the end of Smith's Compleat System of Opticks, 116; Cambridge 1738.

[2] Treatise on Optics, 121; London 1775.

[3] Précis élémentaire de Physiologie, i. 63; Paris 1816.

[4] Mémoires de Mathematique et de Physique, 295; Paris 1694.

[5] Ib. 301.

[6] De Oculis Leucaethiopum et Iridis Motu, 22; Goettingae 1786.

[7] Scheiner, Oculus, 41; Oeniponti 1619.

[8] Op. cit. 298.

[9] Treatise on the Eye, i. 395; Edinburgh 1759.

[10] Lectures on Natural Philosophy, ii. 575; London 1807.

[11] In Dr Young's optometer, as it is usually constructed, a convex lens of 4 inches focus is placed immediately beyond the slits, so as to produce, by a few inches upon the optometer, the effect of a long line; while, by means of a graduated scale and index, the focal length of the sound eye, or of the eye that has become presbyopic, may be determined, as well as the focal length of spectacles required for presbyopic eyes. When the focal length of a myopic eye is to be measured, the convex lens is removed, and a different scale is employed.

[12] Magendie, Journal de Physiologie, iv. 260; Paris 1824.

[13] Op. cit. ii. 3.

[14] Handbuch der Physiologie des Menschen, ii. 326; Coblenz 1836.

[15] Luchtmans de Mutatione Axis Oculi secundum diversam Distantiam Objecti, 70; Trajecti ad Rhenum 1832.

[16] Philosophical Transactions for 1794, 212.

[17] Ib. for 1795, 2.

[18] Ib. for 1796, 2.

[19] Ib. for 1801, 54.

[20] Ib. 55.

[21] Medical Essays and Observations, by a Society in Edinburgh, iv. 150; Edinburgh 1752.

[22] Philosophical Transactions for 1801, 67.

23 Select Works of Antony van Leeuwenhock, translated by Hoole, i. 232; London 1800.

24 De Facultate Oculi, qua ad diversas rerum conspectarum Distantias se accommodat; Lugduni Batavorum 1719. In Haller's Disputationes Anatomicæ, vii. pars ii.

25 Philosophical Transactions for 1794, 21.

26 View of the progress and present state of Animal Chemistry, translated by Brunnmark, 89; London 1813.

27 Three Treatises. On the Brain, the Eye, and the Ear, 138; Edinburgh 1797.

28 Op. cit. i. 446. Medical Essays and Observations by a Society in Edinburgh, iv. 160; Edinburgh 1752.

29 Edinburgh Journal of Science, i. 79; Edinburgh 1824.

30 Philosophical Transactions for 1796, 8.

31 Synopsis of the Diseases of the Eye, 66; London 1820.

32 London Medical Gazette, xiii. 631; London 1834.

33 Abbildungen des menschlichen Auges, Tab. viii. fig. 4; Frankfurt am Main 1801.

34 Philosophical Transactions for 1822, Pl. vi, fig. 3.

CHAPTER XII.

FUNCTIONS OF THE IRIS. MOTIONS OF THE PUPIL.

§ 105. *Functions of the iris.*

Some of the principal functions of the iris (7, fig. 3), have already demanded our attention. We now require to take a connected view of those functions, and of the means by which the motions of the iris are supposed to be performed.

1. The simplest view which can be taken of this part of the eye is, that it is an opaque disk, perforated near its centre, so as to transmit through its aperture, the *pupil*, a certain quantity of the light which radiates from external objects, while it excludes the rest. It thus secures the formation of images of sufficient brightness, or, more correctly speaking, the production of impressions of sufficient force, upon the retina, (§ 8, 9.)

Had there been no iris, or had the pupil been much larger than it is, the eye would have no longer served as a *camera obscura*, but would have been over-illuminated; the images on the retina would therefore have been diluted or obliterated, and vision would have been rendered extremely indistinct or been altogether prevented. Had the pupil been much smaller than it is, the images on the retina would no doubt have been well defined; but the quantity of light would have been insufficient to produce the necessary impressions, and our sensations consequently have been faint and indistinct.

2. An obvious and important function of the iris, is, by the contraction and dilatation of the pupil, to regulate the quantity of light admitted into the eye. The iris is a photometer, contracting its aperture when the light is bright, so that a part of it may be intercepted, and opening its aperture when the light is feeble, so that more of it may enter; thus regulating the light, in such a manner that, in all cases, the retina may receive the quantity best suited for producing the necessary impressions.

3. A third use of the iris is, that it serves as a diaphragm or stop, excluding a great proportion of the rays which have traversed the circumferential portion of the cornea, and would pass too near to the edge of the crystalline. It thus lessens the spherical aberration of the eye. (§ 62, 63.)

4. The iris, as a diaphragm, by limiting the aperture of the eye, diminishes the amount of chromatic aberration. It is those rays which pass through a lens near its edge, which suffer the greatest dispersion, and these are arrested by the iris. (§ 73.)

5. The pupil dilates when the eye is directed to a distant object, and contracts when the object is near. (§ 86.) This happens although the near object is dimly seen, and the distant one well illuminated, so that this function of the iris is independent, within certain limits, of the quantity of light to which the eye is exposed. By the contraction of the pupil, the rays which diverge too much to be brought to foci on the retina are excluded, and thus our vision of near objects is rendered more distinct. By the expansion, a sufficient quan-

tity of light is admitted, without which the remote object would appear obscure. The aperture of the eyelids is contracted and expanded at the same time with the pupil, and for the same purposes. This function is also associated with the changes in the refractive power of the eye, by which it is adjusted to distances.

6. The pupil, as Fontana[1] first observed, is greatly contracted during sleep. It is actually smaller in that state than it would be if the person were awake and his eyes exposed to the most brilliant light. The final cause of the exclusion is probably to ensure rest, and prevent the bad effects of a sudden influx of light into the eyes of one who is asleep. This function is associated with the motion of the eyeball upward and inward, which takes place whenever we close our eyes, and which depends on the action of the inferior oblique muscle. If the subject of observation is awaked, the pupil suddenly expands, and then contracts to a size proportionate to the intensity of the light.

§ 106. *Iris not the organ of adjustment.*

That a connexion exists between the motions of the pupil and the changes in the refractive parts of the eye by which it is adjusted to distances, is generally admitted. Mile, Pouillet, and Treviranus, however, have supposed the motions of the pupil to be the direct means of adjustment.

1. Mile[2] is of opinion, that the adjustment of the eye for *continued* distinct vision, is effected by the inflection or diffraction of the light[3] at the pupillary margin of the iris, by which he thinks there will be formed, instead of one focus of each luminous point, several foci, arranged in a line of some extent, so that the object may within certain limits change its distance, and yet one of these fall upon the retina. The focal length he conceived to be in an inverse ratio to the size of the pupil. The *momentaneous* distinct vision of objects at different distances, again, he supposes to depend on a change in the curvature of the cornea, produced by the iris in the act of contracting the pupil.

2. Pouillet[4] regards the central laminæ of the crystalline, as more convex, as well as more dense, than those which lie near the circumference. (§ 50). Hence, he considers the crystalline as a lens, not with one focus, but an infinity of foci. Observing that the pupil contracts when the eye is directed to near objects, he concluded that then the central rays only will pass through the crystalline, and, being refracted by its central portion, will be brought to foci, and form the image on the retina; but, that in regarding distant objects the image will be formed by the peripheral rays, admitted through the dilated pupil, and through the circumferential part of the crystalline. In the latter case, the central rays will meet in the vitreous humour and afterwards form indistinct luminous circles on the retina, which (Pouillet thinks) will go for nothing, on account of the greater comparative brightness of the image formed by the peripheral rays.

3. Treviranus[5] also considers the changes in the size of the pupil, along with the unequal density of the crystalline, as effecting the adjustment of the eye to distances. According to his calculations, the crystalline will collect into foci the rays from objects at every distance, provided the size of the pupil be such as to modify, in accordance with a law which he states, the proportion between the central and peripheral rays.

To each of these hypotheses numerous objections might be made; to all the three may be opposed the two following observations by Volkmann;[6] viz. *first*, that were the adjustment to distances a direct effect of the motions of the iris, then any change in the size of the pupil produced by a variation in the intensity of the light ought to disturb the state of adjustment, which is not the case; and, *secondly*, that the power of adjustment continues although the pupil is motionless, or, which is equivalent to the pupil being motionless, although the object be viewed at different distances through a pin-hole.

§ 107. *Size of the pupil does not affect the size of the image.*

The images formed by simple radiation (§ 8) vary in size,

according to the size of the aperture of transmission; but it is otherwise with regard to the images formed by refraction. The eye being accommodated to the distance of an object, the magnitude of the pupil has no influence on that of the image; for the rays of each pencil being always united in the axis of the pencil, (fig. 58), they will fall on the same point of the retina, whether the pupil be contracted or dilated. The visual angle, therefore, under which the object is seen, (§ 55) will be the same in both cases, and of course the apparent magnitude of the object will be unchanged.

If the object, however, be placed without the limits of distinct vision, it will appear greater or smaller, according as the pupil is dilated or contracted; for the rays from the extremities of the object, instead of being united in a point in the axis of each pencil, will now be scattered over a circular space all round that axis, (fig. 79.) which space being greater or smaller according to the size of the pupil, the image will also vary in the same proportion.

To show that this is agreeable to experience, Porterfield[7] observes, that a candle, which, at 60 feet distance, commonly appears to a short-sighted person a luminous circle of about a foot in diameter, more or less, according to the degree of myopia, and the magnitude of the pupil, if viewed through a small hole in a card, seems much less than to the naked eye. The luxuriancy of the image is corrected by the smallness of the aperture, which has the same effect on it that a contraction of the pupil would have. In like manner, the stars, which to most people appear larger than they ought, because the eye with respect to them is somewhat myopic, seem much less, by being viewed through a pin-hole.

§ 108. *Effects of the form of the pupil.*

In by far the greater number of animals the pupil is circular, and preserves this form in all its degrees of dilatation and contraction. This is well known to be the case in the ape-tribe, dog-tribe, the rodentia, and in almost all birds. In the ruminantia and solipeda, the pupil is transversely oblong, both

in the state of dilatation and contraction. In the cat-tribe the pupil when dilated is circular; when contracted, it assumes the form of a perpendicular slit. The experience of the surgical student teaches him that the form of the pupil is not essential to distinct vision, for he sees it become permanently misshapen and denticulated from inflammation, and yet vision preserved; while in cases of closure of the natural pupil, he knows that vision is sometimes restored by the formation of an artificial pupil, which is oftener triangular or quadrangular than circular. The simple experiment of transmitting the light of a candle, through apertures of different forms, shows that the figure of the image is not affected by the figure of the aperture; and so it is in the eye.

Three advantages of a circular pupil are pointed out by Porterfield.[8]

1. A circle being the most capacious of all figures, a circular pupil must transmit the greatest quantity of light, by which means the impressions on the retina will be more lively than they could have been, had the pupil been of any other figure.

2. As no spherical surface can accurately refract all the rays of a large pencil to a point, but only those near its axis, there must always be a tendency to confusion in the images on the retina from the form of the surfaces of the humours, and a still greater tendency to confusion from a too great distance or proximity of objects. The confusion from both cases will be lessened by the circular figure of the pupil, because all the rays are thereby brought as near to the axis of their several pencils as possible.

3. By means of the circular figure of the pupil, the eye is able to see equally well in every direction. In those animals whose chief occupation it is to seek their food with their heads bent down towards the earth, the pupil is oblong, with its greater diameter towards the angles of the eye, that it may receive the rays from the objects immediately before the animal, and on each side. The perpendicular pupil of the cat-tribe equally fits them for seeing best upward and downward, which their habits of climbing and descending require.

The cat, opening its pupil wide, during the night, makes it assume a circular form, so that it takes in as much as possible of the faint rays reflected from the surrounding objects; but during the day, it draws its pupil into a narrow slit, and by shutting its eyelids contracts this slit so as to admit only the smallest beam of light. The animal is thus enabled to see, and to pursue its prey, both by day and night.

§ 109. *Surface of the iris plane. Centres of the iris and pupil not coincident.*

The pupil has no fixed determined measure, but varies in diameter according to circumstances, from $\frac{25}{100}$dths to $\frac{12}{100}$dths of an inch. Seen through the cornea and aqueous humour, it appears larger than it is in reality. If we put the eye of an animal into a vessel of water, the effect of the convex surface of the cornea being thereby removed, the pupil is seen of its natural size. This method of viewing the eye serves also to show that the human iris is plane, and not convex, as some have supposed. The eye which is so examined must be quite recent, for if it has lain some time, so as to have become flaccid from evaporation of its fluid parts, and has then been put into water till it becomes plump again, water is absorbed through the foramina of the sclerotica, and pushing the lens and iris towards the cornea, gives the iris an unnatural convexity.

The effect of the aqueous humour and cornea in magnifying the pupil and making the iris appear convex, may be illustrated by drawing on a card a figure of the iris and pupil of the size of a common watch-glass, filling the watch-glass with water, covering it with the painted part of the card, and then inverting it, so as to view the iris and pupil through the water and the watch-glass.

When explaining (§ 54) the meaning of the phrase *optic axis*, we pointed out the want of correspondence between the centre of the iris and that of the pupil. They approach nearer to one another in the contracted state of the pupil, and divaricate more when the pupil dilates. The iris is

broadest in the direction downward and outward, and narrowest in the opposite direction.

§ 110. *Natural state of the pupil.*

Although the pupil is sometimes found dilated, after death, and in other instances contracted, it is generally in a medium state (§ 104); and this, I conceive, should be regarded as its natural state, or the state of relaxation, into which it will fall when free from every kind of excitation. The common notion, however, founded upon what takes place when the eye is withdrawn from the stimulus of light, and again exposed to it, is, that the natural state of the pupil is a state of dilatation, and its contraction a state of exertion; while Fontana, from finding the pupil almost closed and quite immoveable in sleep, inferred that an expanded state of the iris was its natural state, or state of repose. His argument is not conclusive, for it is well known that the action of involuntary organs continues during sleep. Weber[9] remarks, that the sphincter ani and the sphincter of the bladder resist the fæces and the urine more during sleep than while we are awake; and from this cause, the bladder often becomes distended during the night to a degree far beyond what it can endure during the day. Nature having taken care, partly by a closure of the eyelids, to exclude the light during sleep, and partly by a similar closure of the pupil, we are not warranted to conclude that the latter is any more the effect of an absolute relaxation than the former.

§ 111. *Light has no direct effect on the iris. Iris affected by light, only through the medium of the retina, optic nerve, brain, and third nerve. Motions of the pupils in some cases of complete amaurosis. Consentaneous motions of the pupil of an amaurotic eye with those of the pupil of the sound eye.*

Fontana showed, that though the pupil, when the animal is awake, expands and contracts according to the intensity of the

light to which the eye is exposed, light has no direct effect on the iris. He took a hollow cone of pasteboard, blackened internally, the apex perforated by a hole $\frac{1}{2}$ line in diameter, and the base surrounded by a broad disk, and placing a lighted candle at the base, he directed the apex of the cone towards the eye. If the pencil of light fell upon the iris, no movement of the pupil followed, but if it was directed through the pupil, even without being allowed to touch the iris, the pupil instantly contracted. He repeated the experiment on the eye of a cat, on that of a dog, and on the human eye, with candle-light, and with sun-light, and even with the light concentrated by means of a lens; but in no instance did the iris appear irritable, even in the slightest degree, to the direct stimulus of light.

As the crystalline and the vitreous humour, through which the light passes to the retina, are insensible and destitute of irritability, the conclusion to be drawn from such experiments as those related by Fontana, is, that the motions of the pupil, which arise from variations in the intensity of the light, depend on the action of this stimulus on the retina. The question has naturally occurred, whether there is any communication between the retina and the iris. Morgagni[10] imagined, that perhaps the reason why the retina was prolonged as far as the corpus ciliare, was, that it might communicate through that structure, such a stimulus to the iris, as made the pupil contract. Certain facts, which I have observed, render this notion untenable. It is well known, that both during a healthy state of the eyes, and also in several cases of disease, the light which acts directly on the one retina, acts indirectly on the iris of the opposite eye. For example, although the one eye is shaded from the light, its pupil, only in a less degree, continues to contract and expand according to the intensity of the light to which the other eye is exposed. I had under my care a man, one of whose eyes had suffered from a blow, in such a way that the lens was displaced and absorbed, the vitreous humour was dissolved, the retina was opaque and totally insensible, and having become detached from its adhesion at the ora serrata, floated forward and backward in the eye every time

the man moved his head. The pupil of this eye contracted and expanded with vivacity, according to the degree of light to which the opposite sound eye was exposed; a fact sufficient to set aside the conjecture of Morgagni.

Experiments on animals, together with pathological observations, sufficiently prove the following particulars:—

1. That the motions of the pupil require a sound state of one or other retina.

2. That the motions of the pupil require the third nerve or motor oculi of the same side, to be in a sound state.

3. That the motions of the pupil require a certain communication to be kept up, between one or other retina and the brain, and between the brain and the third nerve of that side to which the eye belongs whose pupil is to be moved.

The experiments to which I refer were performed by Mr Mayo;[11] and are as follows:—

1. If the optic nerves be divided within the cranium of a living pigeon, the pupils become very large and motionless.

2. If the trunk of the third nerve, which in birds supplies the whole of the ciliary or iridal nerves, be divided within the cranium of a living pigeon, the pupil dilates and cannot be made to contract by exposure even to intense light.

3. When the optic nerves are pinched within the cranium of a living pigeon, the pupils contract.

4. In the living or dead bird, the same result follows a similar irritation of the third pair, but not that of the fifth.

5. When the optic nerves have been divided within the cranium of a pigeon immediately after decapitation, if the portion of the nerves attached to the eyes be pinched, no contraction of the pupil ensues; but if the portion adhering to the brain be pinched, a like contraction of the pupil is produced as if the optic nerves had not been divided.

6. If the third pair has been divided, no change in the pupil ensues on irritating the entire or divided optic nerves.

From these facts, it may fairly be concluded, that in the motions of the pupil, an impression is conveyed from the retina, along the optic nerve to the brain, which is followed

by a reflex affection of the third nerve, causing the pupil to contract or dilate.

Numerous pathological observations prove that the brain may so suffer from disease, as to be incapable of acting as the organ of visual perception, and yet retain the power of communicating to the third nerve the impulse necessary for the usual motions of the pupil. The idea[12] of the iris acting in such cases, by a sympathy with the retina, independent of the brain, is altogether contrary to the physiology of the iris, as founded on experiment. The following explanation of the fact, I published in 1830, in the first edition of a *Practical Treatise on the Diseases of the Eye.*

If we suppose that vision is accomplished only where the optic nerves reach the corpora quadrigemina, and thus communicate with the posterior part of the medulla oblongata, but that the association which undoubtedly exists between the optic nerves and the third pair, is effected farther forward on the basis of the brain, we shall be able to afford at least a plausible explanation of the fact of the lively mobility of the pupils in certain cases of complete amaurosis. The third pair makes its appearance immediately behind the tuber cinereum, a part of the brain with which the optic nerves have a manifest connexion. The third pair does not, indeed, appear to take its origin from the tuber cinereum, but from the central cineritious substance of the crura cerebri, bearing an analogy, along with the sixth and ninth pairs, the portio dura of the seventh, and the portion of the fifth which escapes the Gasserian ganglion, to the anterior roots of the spinal nerves; but it is surely not an improbable supposition, that the optic nerves, either where they cross the crura cerebri, or, more probably, where they communicate with the tuber cinereum, form that link of connexion with the third pair, which they are universally acknowledged to do in some part or other of their course. Disease, then, affecting the corpora quadrigemina, or, in other words, the origin of the optic nerves, or affecting any part of the tractus opticus between the corpora quadrigemina and the communication between the optic nerves and the third pair, wherever that communication is effected,

will, according to this view of the subject, produce blindness, but may leave unimpaired the influence of the optic nerves upon the third pair and upon the motions of the pupils.

This explanation receives no inconsiderable support from a case, recorded by Mr Travers,[13] of a circumscribed tumour, compressing the left optic nerve, immediately behind the ganglion opticum, by which I suppose he means the thalamus. In that case, the blindness was complete, but the iris was active. Amaurosis, with lively pupils, has not unfrequently been found to depend on disease of the cerebellum.[14] Cases of amaurosis, on the other hand, in which the pupils are dilated and immoveable, are probably owing, either to more extensive disease, or to disease so situated as to affect that part of the brain where the optic nerves communicate their influence to the third pair.

If the above be the true explanation of the activity of the pupils, which sometimes exists in cases of total blindness, it will also account for the motions of the iris of an amaurotic eye, when the opposite and sound eye is exposed to various gradations of light. The right eye, we shall say, is healthy; but the left, from some change in the retina, or in that portion of the optic nerve which extends from the retina to the point of union of the optic nerves, is blind. Still, the right optic nerve, dividing at the chiasma into two portions, one to the right and the other to the left side of the brain, is in communication with both nerves of the third pair, so that although the pupil of the blind eye becomes expanded and fixed when the sound eye is shut, it instantly contracts when the sound eye is exposed to light, and so long as this is the case, performs exactly the same motions. This view of the matter is confirmed by the case which I have already mentioned, in which the retina, in consequence of an injury, was insensible, opaque, and detached from its natural adhesion to the choroid. When the diseased eye was separately exposed to light, its pupil stood fixed and dilated; but when both eyes were open, the pupil of the amaurotic eye moved briskly. There was no reason to believe, that, in this case, there was any part of the nervous apparatus diseased but the retina.

§ 112. *Hypotheses regarding the mechanism by which the pupil is moved. Structure of the iris and uvea. Ciliary nerves. Muscular fibres not detected in the iris. Travers supposes the iris to consist partly of muscular, and partly of elastic tissue. Erectile hypothesis of Mery and Haller. Objections of Fontana and Blumenbach. Contractility of the ciliary nerves observed by Serres.*

Although the immediate mechanism by which the pupil is contracted and expanded, has powerfully excited the attention of physiologists, their inquiries have hitherto led to no decided conclusion. Two hypotheses have been formed on the subject; the one that the iris is a muscular organ, the other that its motions depend on changes in the state of its blood-vessels.

The iris is easily divided into two laminae, an anterior, which is the proper *iris*, the *tunica cærulea* of the old anatomists, and a posterior, which the moderns style the *uvea.* The latter is of a deep brown colour, approaching to black, consists of pigment similar to that which lines the choroid, and is evidently intended to render the iris, as a diaphragm, impervious to light. The uvea presents minute folds or plaits, running from its ciliary towards its pupillary edge. Similar plaits are visible on the posterior surface of the iris, when the uvea is cautiously removed. The iris, as seen through the cornea, is generally of a bluish or hazel colour, and presents two rings, an external or ciliary, which is the broader, and an internal or pupillary, which is the narrower. The anterior surface of the iris is variously striated, and examined under water appears flocculent. The striæ are more or less distinct in different individuals, they are flexuous and parallel in their course from the ciliary towards the pupillary edge of the iris, and are generally described as prolongations of the ciliary nerves. Where the external ring joins the internal, or about $\frac{1}{20}$ inch from the pupil, the striæ form a knotted anastomotic wreath, whence still more minute striæ are continued in parallel lines to the edge of the pupil. The generality of the belief that the striæ observed on the iris, are prolongations of the ciliary

nerves appears to be in a great measure owing to their being so represented by Zinn,[15] in a beautiful engraving, which has been often copied. Young,[16] and more recently Arnold,[17] have, as well as Zinn, traced the ciliary nerves through the annulus albidus to the iris. Others, such as Eble,[18] have failed to trace any such connexion, and have urged that the striæ or fasciculi on the anterior surface of the iris, are much larger and more numerous than the ciliary nerves, and that when examined with fine needles under the microscope, they bear no resemblance to nerves. Dr Jacob compares them to the chordæ tendineæ of the heart. It is remarkable that even those who profess to have traced the ciliary nerves into the iris, do not say that the fasciculi, easily seen with the naked eye on the iris, are really continuations of the ciliary nerves.

The ciliary or iridal nerves, 12 to 18 in number, are derived from the lenticular ganglion, which lies between the rectus externus muscle and the optic nerve, and is formed by a long filament from the nasal branch of the ophthalmic or first division of the fifth nerve, and a short twig from the inferior branch of the third nerve or motor oculi. This is the motive root, and the other is the sensitive root of the ganglion. Having penetrated through the posterior part of the sclerotica, the ciliary nerves, which are the branches given off by this ganglion, advance between the sclerotica and choroid, till they reach the annulus albidus, where each of them bifurcates.

The iris is abundantly supplied with blood-vessels, not only from two arteries, called the long ciliaries, which are peculiarly destined to it, but from the arteries of the ciliary processes internally, and from the anterior ciliaries externally.

If we divide the eye into an anterior and a posterior half, remove the vitreous humour and crystalline, cut away the cornea, wash away the pigment forming the uvea, and, suspending the iris in water, hold it up to the light, it appears thin and semitransparent, except near the pupil, where it presents a ring of about $\frac{1}{40}$ inch broad, thicker and consequently less transparent than the rest of the membrane. This ring does not reach quite to the edge of the pupil. It is easy to conceive, that the appearance of this ring may have led some

anatomists to suppose they had discovered a sphincter muscle for closing the pupil.

When I view the iris, thus prepared, with my back to the light and the sun's rays falling upon the membrane, I see abundance of white striæ running from its external circumference towards the pupil, and they appear still more numerous and distinct when viewed through a lens of short focus. A careful examination shows that the greater number of these striæ are blood-vessels. The rest are the white fasciculi seen during life, and supposed to be the ciliary nerves. No other radiating fibres have been seen; and no orbicular fibres whatever.

The hypothesis adopted by Monro,[19] Maunoir,[20] Home,[21] and others, that the iris contains two sets of muscular fibres, the one set radiating from its ciliary edge towards the pupil, and serving by their contraction to expand the pupil, while the other set surround the pupil as a sphincter, and close it by their contraction, would completely explain not only the motions of the pupil in health, but also such diseases as *myosis*, in which the pupil is contracted and cannot expand, and *mydriasis*, in which it is dilated and cannot contract. The motions of the pupil are sudden, like those produced by muscular action. The motive nerves, derived from the motor oculi, which anatomists describe as so abundantly distributed to the iris, can scarcely be supposed to serve any other purpose than to stimulate muscular fibres, as all the other motive nerves do throughout the body. The substance of the iris is very thin, and as there is no positive external appearance by which we can distinguish muscular fibres, this membrane may still contain such fibres, although those who have supposed they had detected them, had in reality seen only blood-vessels and nerves. Maunoir even mentions that the radiating fibres, which he detected in the human iris, were hollow; a circumstance sufficient to show that they were vessels, and not muscular fibres. Sir Everard Home describes the iris as consisting of two laminæ; an anterior which is vascular, and a posterior which is muscular; but it is plain that what he styles "bundles of muscular fibres" are merely the plaits already mentioned, which are seen

on the posterior surface of the iris, when the uvea is removed, and which correspond to the plaits of the uvea itself. The iris being supported by the aqueous humour, will require a much less force to move it, than if it were suspended in air, and hence the muscular fibres may be so fine as hitherto to have escaped detection. In an iris prepared in the manner already described, I discern the blood-vessels with my naked eye. They probably measure, therefore, considerably more than $\frac{1}{1000}$ inch in diameter; but its muscular fibres, if it possess such, must be at least seven or eight times less than this.

Haller[22] showed that the iris is not irritable to mechanical stimuli. Fontana and others repeated Haller's experiments, pricking the iris with a needle introduced through the cornea, without exciting any motion. This proves nothing; for even the muscular coat of the stomach cannot be made to contract by the strongest mechanical stimuli.[23]

Nysten[24], by the application of Galvanism to the dead bodies of criminals soon after death, succeeded in making the pupil contract; although in the hands of others, the experiment has generally failed. But, as Magendie[25] remarks, the retina, as well as the iris, is submitted in such experiments, to the Galvanic influence, and there is no evidence that the contraction of the pupil is not an effect of the irritation produced in the retina.

As a modification of the muscular hypothesis, may be noticed the opinion of Mr Travers[26], that the pupillary portion of the iris is a sphincter, and the ciliary an elastic structure. He supposes, that in the iris, as in some other parts of the body of animals, elasticity is opposed to muscular action. Hence, when the sphincter of the pupil is paralyzed, as he considers it to be by the influence of the belladonna, or when the nervous stimulus by which the muscle should be called into action is intercepted, as in some cases of amaurosis, the elastic force predominates, and the pupil becomes dilated and fixed.

Mery[27] supposed the dilatation of the pupil to be entirely the effect of the elasticity of the straight fibres of the iris,

which he describes as terminating at its pupillary edge. The contraction of the pupil he ascribed to a flow of the animal spirits into the same fibres, caused by the influence of the light upon the retina. His notions regarding the nature of the fibres seem to have been vague and unsettled; for while he speaks of them as being elongated by receiving an additional quantity of the animal spirits, which would lead us to suppose that he considered the fibres to be nerves, he hints that their structure is probably the same as that of the corpora cavernosa.

Haller[28] was equally unsuccessful as Mery in detecting circular fibres around the pupil. His experiments led him to believe that as the iris was not irritable, it could not be muscular. He therefore adopted the hypothesis of Mery, that its structure was erectile, with the slight alteration, as he himself mentions, that instead of attributing the elongation of the fibres to a flow of the animal spirits, he considered the cause to be a sudden congestion, by which the serpentine folds of the vessels and cellular tissue are expanded. He compares[29] this extension of the iris to what happens in blushing, orgasm of the genital organs, and inflammation ; and as the objection naturally occurred to him of the suddenness with which the pupil contracts under the stimulus of light, he urges the activity of the nervous power, and the extreme shortness of the vessels in which the congestion takes place.

Few physiologists have regarded Haller's hypothesis as satisfactory. Amongst the numerous objections which have been made to it, I may mention one by Fontana, and another by Blumenbach.

Fontana[30] objects, that the finest and most penetrating injections, thrown into the arteries even immediately after the death of an animal, never produce any extension of the iris, like what happens to the corpora cavernosa.

Blumenbach[31] directs our attention to the transparent iris of the albino and white rabbit, in which, when the pupil contracts, no appearance of congestion, nor any change of colour, is discernible.

Fontana embraces neither the muscular nor the erectile

hypothesis. The motion of the iris is much too great, he thinks, to be executed by the contraction and relaxation of radiating muscular fibres; for the iris, when the pupil closes in sleep, is thirty times broader than it is when the pupil is in its state of greatest expansion. No muscular fibre, he urges, can shorten itself to this extent. In warm-blooded animals, there is no muscle which shortens itself one half; and even polypi, in their state of greatest length, are never more than twelve times longer than in their state of greatest contraction. His notion is, that expansion of the iris is its natural state, that it then contains a determinate quantity of blood, and that this quantity becoming lessened in a way which he pretends not to explain, the iris contracts.

So much puzzled was Blumenbach by the physiology of the iris, that, instead of unravelling, he cut the knotty question, and referred the motions of the pupil to what he styles a *vis iridis propria*.

A curious property of the ciliary nerves was observed by Serres.[32] If we open the eye of an animal, and remove one of the ciliary nerves, which we find between the sclerotica and choroid, as soon as we lay hold of one of its extremities with a pair of forceps, the nerve coils itself up, so that in a few seconds it is reduced to $\frac{1}{20}$th of its natural length. If we now plunge it into water, it resumes its former length; but, on lifting it out again, it twists itself together as before. Serres concludes from this fact, that the ciliary nerves being continued into the iris, it is by this contractile power, that the pupil is expanded. In support of this hypothesis, he notices the fact, that those animals in whom the pupil is motionless, as the frog, have no ciliary nerves.

§ 113. *Motions of the pupil involuntary, but rendered apparently voluntary by an effort at adjustment.*

The Stahlians, among whom was Porterfield, believed the motions of the pupil to be voluntary. It is unnecessary to refute a doctrine, which probably has no longer a single supporter.

An apparently voluntary motion of the pupil is observed in the cat, the parrot, and some other animals. But when these animals move their pupils independently of any change in the intensity of the light to which their eyes are exposed, it is more likely that the motion arises from some instinctive affection of the animal, than from volition.

The human eye sometimes acquires a power by which the iris is moved apparently by an act of the will.[33] But in such cases, the pupil contracts merely because the person makes an effort as if to see a near object, and it expands again on his allowing the eye to resume the state in which it is fitted for distant vision. The contraction of the pupil, in this sort of experiment, is attended by a convergent motion of the eyeballs; and the dilatation, by a return of the optic axes to a parallel position.

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[1] Dei Moti dell' Iride, 22; Lucca 1765.

[2] Journal de Physiologie par Magendie, vi. 197; Paris 1826.

[3] Of the light which proceeds past a dense substance of any kind, by far the greater part pursues its rectilineal course undisturbed, but a small portion diverges in every direction. This effect, which is generally attended by the production of coloured fringes, was first described by Grimaldi, and was called by him *diffraction*. Newton called it *inflection*. The shadows of bodies, placed in the diffused cone, formed by a pencil of light admitted through a small hole into a darkened chamber, are magnified, and fringed with colours, by inflection. It has generally been admitted that some inflection of the rays may take place in passing the edge of the pupil; but that its great mobility, its considerable size, and its very small distance from the crystalline, should prevent any confusion from this cause. When the pupil is much contracted, and the iris possesses little or no motion, some confusion may arise from inflection.

[4] Elémens de Physique expérimentale et de Météorologie, ii. partie i. 331; Paris 1829.

[5] Beiträge zur Aufklärung der Erscheinungen und Gesetze des organischen Lebens, heft i; Bremen 1836.

[6] Neue Beiträge zur Physiologie des Gesichtssinnes, 127; Leipzig 1836

[7] Treatise on the Eye, ii. 181; Edinburgh 1759.

[8] Ib. 87, 267.

[9] De Motu Iridis, 49; Lipsiæ 1821.

[10] Epistolæ Anatomicæ ad Scripta pertinentes Valsalvæ, Ep. xvii. § 48; p. 304; Venetiis 1740.

[11] Anatomical and Physiological Commentaries, No. ii. 4; London 1823.

[12] Travers' Synopsis of the Diseases of the Eye, 188; London 1820.
[13] Ibid.
[14] Andral, Clinique Médicale, v. 682, 693, 710; Paris 1833.
[15] Descriptio Anatomica Oculi Humani, Tab. iv. fig. 1; Gœttingæ 1780.
[16] Philosophical Transactions for 1801, 74; Pl. vi. fig. 47.
[17] Anatomische and Physiologische Untersuchungen über das Auge des Menschen, 78; Taf. ii. fig. 2; Heidelberg 1832.
[18] Ammon's Zeitschrift für die Ophthalmologie, ii. 173; Dresden 1832.
[19] Three Treatises. On the Brain, the Eye, and the Ear, 111; Edinburgh 1797.
[20] Mémoires sur l' Organisation de l'Iris et l'Operation de la Pupille Artificielle, 4; Genève 1812.
[21] Philosophical Transactions for 1822, 78; Pl. vi. fig. 8, Pl. vii. fig. 1.
[22] Opera Minora, i. 372; Lausannæ 1762.
[23] Müller's Handbuch der Physiologie des Menschen, i. 489; Coblenz 1835.
[24] Recherches de Physiologie et de Chimie Pathologiques, 314, 319, 324; Paris 1811.
[25] Précis Elémentaire de Physiologie, i. 66; Paris 1816.
[26] Op. cit. 63.
[27] Mémoires de l' Académie Royale des Sciences pour 1704, 261; Paris 1706.
[28] Elementa Physiologiæ, v. 371, 378; Lausannæ 1763.
[29] Opera Minora, i. 233.
[30] Op. cit. 98.
[31] De Oculis Leucaethiopum et Iridis Motu, 33; Gœttingæ 1786.
[32] Anatomie Comparée du Cerveau, ii. 652; Paris 1827.
[33] Travers' Op. cit. 72. Purkinje's Beobachtungen und Versuche zur Physiologie der Sinne, i. 123; Prag 1823.

CHAPTER XIII.

REFLECTION OF LIGHT BY THE EYE.

§ 114. *Second law of light. Its reflection from plane, convex, and concave surfaces. Spherical aberration of mirrors.*

Light, falling upon certain surfaces, is reflected from them, and, in such cases, the angle of reflection is always equal to

the angle of incidence. (§ 4, 5.) This is the second of the laws of light (§ 3); and holds true, whether the reflecting surface is plane, convex, or concave.

Optical instruments which operate on light by reflection are called *catoptric* instruments, from κατὰ, *against*, and ὀπτομαι, *I see.*

Any catoptrical phenomena, manifested in the eye, are merely incidental and unavoidable; and we shall have occasion by and by to examine a contrivance in this organ, evidently intended to prevent reflection.

As the cornea and the anterior crystalline capsule act as convex mirrors, and the posterior crystalline capsule as a concave mirror, it is necessary that we should explain shortly the formation of images by reflecting surfaces.

1. *Plane reflecting surface.* Images formed by plane reflecting surfaces, are equal and similar to the objects; and appear at the same distance behind the plane, that the objects are before it.

Let M R, fig. 84, be a plane mirror, O B an object placed before it, and E the eye of an observer, situated anywhere in front of the mirror. Out of the rays flowing in every direction from the object, only a few can be so reflected as to reach the eye at E. Those which do reach it, such as O D, B G, are reflected from points, D, G, of the mirror, so situated in relation to the object and the eye, that the angles of incidence and reflection are equal.

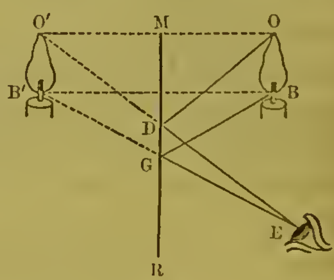

Fig. 84.

From the point O, draw a perpendicular, O M, meeting the reflecting surface in M, and prolong this perpendicular indefinitely beyond the other side of the mirror. Continue the reflected ray D E backwards, till it intersects this perpendicular in O′, and O′ will be the virtual focus (§ 4.) of the rays emanating from O, and which by reflection enter the eye at E. The intersection of a similar perpendicular drawn from B, by the reflected ray G E continued backward, will determine the

place of B′, the virtual focus of rays emanating from B and reaching the eye by reflection. The lines O O′, B B′, being equal and parallel, the virtual image, O′ B′, will have the same size and distance behind the mirror, that the object, O B, has before it.

Since the mirror stands half-way between the object and the image, the image, measured on the surface of the mirror, will equal half the real dimensions of the object, at whatever distance it is placed. If the student takes the breadth of the image of his own cornea, with a pair of compasses, placed on the surface of any plane upright mirror, he will find it to be about $\frac{9}{40}$ inch, which is $\frac{1}{2}$ the actual breadth of the cornea. Hence, the height of an upright mirror, in which a man may view his whole person, must be half his height.

2. *Convex reflecting surface.* Images formed by a convex reflecting surface, always appear behind it; they are erect, and smaller than the objects which they represent. The greater the convexity of the reflecting surface, or the shorter its radius, the image appears the nearer and the smaller.

Let M R, fig. 85, be a convex mirror, whose centre of curvature is C; O B, an object placed before it; and E, the place of the eye. If we draw the lines C O, C B, from the centre of the mirror to the extremities of the object, and continue the reflected rays D E, G E, backward, till they intersect the lines C O, C B, we shall determine the virtual foci, O′ and B′. The virtual image, O′ B′, is always within the lines C O, C B, and is consequently less than the object.

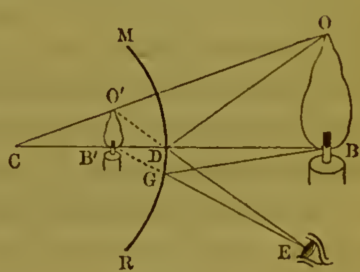

Fig. 85.

The image approaches the mirror as the object approaches it, and recedes as the object recedes. When the object is at the distance of half the radius in front of the mirror, the image is at one-fourth of the radius behind it. When the distance B D equals the radius, the distance D B′ equals one-third of it. When the object is infinitely distant, so that the rays falling on the mirror are parallel, the image is at the principal focus,

which is at the distance of half the radius. With regard to the size of the image, in approaching the mirror, the image and object approach to equality; and when they touch it, they are both of the same size. In every other position, objects appear diminished in a convex mirror, the size of the image being to the size of the object, as C B′, the distance of the image from the centre of the mirror, is to C B, the distance of the object.

3. *Concave reflecting surface.* Images formed by a concave reflecting surface appear before it, are positive, diminished and inverted; except when the object is placed nearer to the mirror than its principal focus, in which case the image is virtual, magnified, erect, and appears behind the reflecting surface.

Let M R, fig. 86, be a concave mirror, whose centre is C, and let O B be an object placed farther from the mirror than C. The upper extremity of the object, O, sends out a conical pencil of diverging rays, O M, O A, O R, to the whole concave surface of the mirror.

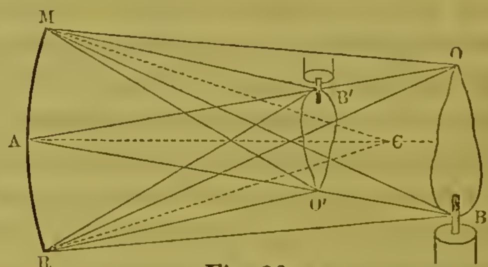

Fig. 86.

A similar pencil flows from B, and from every point of the object. From the centre of concavity, C, draw the three right lines C M, C A, C R, touching the mirror in the same points as the rays proceeding from O and B. Make the angle C M O′ equal to the angle O M C, and the right line M O′ is the course of the ray O M after reflection; make the angle C A O′ equal to the angle O A C, and A O′ is the course of the ray O A after reflection; make also the angle C R O′ equal to the angle O R C, and R O′ is the course of the ray O R after reflection. All these reflected rays will meet in the point O′, where they will form the lower extremity, O′, of the inverted image, O′ B′. If the angles of reflection of the rays emanating from B, be in like manner made equal to their angles of incidence, they will all meet at the point B′, and form the upper extremity of the inverted image, O′ B′. Conical pen-

cils of rays, proceeding from the points of the object intermediate between O and B, will be reflected to intermediate focal points between O′ and B′, so as to complete the diminished inverted image, O′ B′, of the object, O B. As a great number of rays concur in forming each point of the image, it will be very bright.

If the object is at an infinite distance, so that the rays which fall on the mirror are parallel, the focus of each pencil will be at a distance from the reflecting surface equal to half the radius of its concavity. This is called the *principal focal distance.* When the object is brought nearer to the mirror, the incident rays, such as B R, approach to the perpendicular, such as C R, and consequently the reflected rays, such as R B′, will also approach to the perpendicular; and hence the focus of diverging rays, such as B′, will be farther from the mirror than the principal focus, or focus of parallel rays. So long as the object is more remote than C, the size of the image, O′ B′, is to the size of the object, O B, as the distance of the image from the mirror is to the distance of the object.

The points O and O′ are conjugate foci (§ 4). If, then, the object is placed at O′ B′, a magnified and inverted image of it will be formed at O B. If the luminous body is brought still nearer to the mirror, the focus will come forward to meet the luminous body, and at the centre, C, they will coincide; for, in that case, the incident rays, being all perpendicular to the surface of the mirror, will be reflected back upon themselves.

If the object, O B, fig. 87, is brought nearer to a concave reflecting surface, M R, than its principal focus, *f*, as when we look at our face in a shallow concave mirror, the rays, after reflection, will diverge, as if from O′, B′, virtual foci behind the reflecting surface,

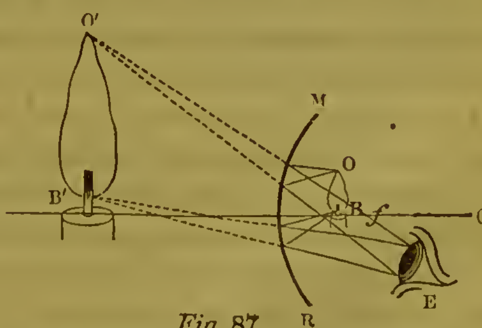

Fig. 87.

and consequently a virtual, erect, and magnified image, O′ B′, will appear to the eye at E.

The simplest of all curved surfaces, the spherical, does not reflect light accurately in the manner above described; for the rays nearest the axis of the reflecting surface are brought to a focus more remote than the focus of rays at a distance from the axis. Mirrors, to be free of aberration, require to be formed in parabolic, elliptic, or hyperbolic curves. If the surfaces of the cornea and crystalline are formed by curves corresponding to those produced by the revolution of conic sections, the images reflected from the eye will be free from aberration. (§ 49).

§ 115. *Images reflected from the cornea and crystalline.*

1. The *white of the eye* is formed by the conjunctiva, tunica tendinea, and sclerotica (§ 2). Its surface, moistened by tears and mucus, reflects the light; but is too irregular to form a distinct image, even of a candle held before the eye.

2. The *cornea* is also bedewed with moisture, and being perfectly regular and polished, reflects an image of any luminous body presented to it. A reflection must take place from its interior as well as from its exterior surface, but the thinness of the cornea renders the interval between the two images so small, that they appear as one. Being formed by a convex reflecting surface, the corneal image is virtual, erect, and diminished, as is seen at once by holding a lighted candle before the eye of any one, and observing the reflection.

3. It was a notion communicated by Mr Ramsden to Sir E. Home,[1] and adopted by Dr Young,[2] that the difference in density between the contiguous media in the eye was so very small, that refraction might take place without reflection. "This appears" says Sir Everard, "to be the state of the eye; for although we have two surfaces of the aqueous, two of the crystalline, and two of the vitreous humour, yet we have only one reflected image, and that being from the anterior surface of the cornea, there can be no surface to reflect it back, and dilute an image on the retina."

This notion is incorrect; for, as was pointed out by Purkinje,[3] there is a reflection both from the *anterior* and the *pos-*

terior surface of the crystalline body. If we move a lighted candle about six inches in front of a healthy eye, a minute inverted image of the flame is seen within the pupil, being reflected from the concave surface of the *posterior crystalline capsule.* If we move the candle to the right, the image is seen to shift to the left; if the candle is raised, the inverted image is seen to descend; and *vicibus versis.* If we withdraw the candle, the image enlarges and grows obscure; if we approach with the candle towards the eye, the image becomes sharp and distinct.

4. Besides the erect image from the cornea, there is a second erect image of the candle, from the *anterior crystalline capsule.* It is not so sharp as the inverted image from the posterior capsule. Being a virtual image, it appears behind the inverted image, which is a positive one; and, being formed by a segment of less curvature, it appears larger. It is even larger than the erect image formed by the cornea, being magnified by the aqueous humour and cornea, through which we see it. Compared, however, to the image formed by the cornea, it is hazy and diffused.

The images formed by reflection from the crystalline body are analogous to those which we see reflected from two watch-glasses, applied edge to edge, or the two surfaces of a double-convex lens, when we interpose between such bodies and the eye a lighted candle. To see the crystalline images distinctly, the subject of experiment, in moderate daylight, and with his back towards the window, should be seated, so that the observer may look rather down into the eye than up, and a candle should be used that burns steadily and does not blaze much. If the pupil is previously dilated by belladonna, the images will be better seen.

The changes which the images, reflected from the eye, undergo in disease, such as, the distortion of the superficial erect image in conical cornea, the disappearance of the inverted image in cataract and in the advanced stage of glaucoma, the enlargement and additional distinctness of the deep erect image in these two diseases, as if by a foil placed behind the reflecting surface, and the total extinction of the deep images, when the

crystalline has been accidentally or artificially displaced, prove of great importance as diagnostic signs. Physiologically considered, such reflections merely prove that a certain quantity of the light, falling upon the refractive media of the eye, is unavoidably lost, which must have the effect of lessening the intensity of the impressions on the retina, although only in an insignificant degree.

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[1] Philosophical Transactions for 1795, 3.

[2] Ib. for 1801, 50.

[3] Commentatio de Examine physiologico Organi Visus et Systematis Cutanei; Vratislaviæ 1823. Ammon's Monatsschrift für Medicin, Augenheilkunde und Chirurgie, ii. 478; Leipzig 1839.

CHAPTER XIV.

ABSORPTION OF LIGHT IN THE EYE. FUNCTIONS OF THE CHOROID AND PIGMENTUM NIGRUM.

§ 116. *Anatomical relations of the pigmentous membrane. Its analogy to the rete Malpighianum. It is colourless in albinous animals. Chemical properties of the pigmentum nigrum.*

The choroid coat and the iris are by far the most vascular parts of the eyeball; presenting, in this respect, a remarkable contrast to the sclerotica and cornea, within which they are contained, as well as to the retina, and to the vitreous and crystalline capsules, which they surround. It is probable that the great vascularity of the choroid and iris is connected with the production of a peculiar substance, by which their whole internal surface is covered. The substance in question is commonly called the *pigmentum nigrum*, although in man it is not black, but of a deep reddish brown, or tobacco colour.

When the eyeball is opened in water, the pigment separates

in the form of a membrane, from the internal surface of the choroid. If a small fragment of this pigmentous membrane is examined with the aid of the microscope, an appearance presents itself such as is represented in fig. 88. The membrane is seen to consist of flat hexagonal corpuscles, connected together by their edges, and each measuring in the sheep about $\frac{1}{1000}$ inch in breadth. In man they are smaller. These corpuscles are nearly transparent at their centre, but are loaded with dark brown matter at their edges.

Fig. 88.

On the internal surface of the corpus ciliare, and especially in the depressions between the ciliary processes, the pigmentous membrane is thick and very dark-coloured, as well as on the posterior surface of the iris, where it constitutes the *uvea*. (§ 112). In this last situation, the pigment is preserved from the contact of the aqueous humour by a delicate transparent membrane, not unlike that discovered by Dr Jacob, between the pigmentous membrane and the retina. The regular hexagonal form of the corpuscles is discernible, only in that portion of the pigmentous membrane, which lies behind the ora serrata of the choroid, and consequently is in contact with Jacob's membrane. In the sheep, I observed that Jacob's membrane was moulded upon the corpuscles, and preserved their impression even after it was separated from the eye, and placed under the microscope.

Believing the pigmentous membrane to be analogous to the rete Malpighianum of the skin, Gmelin[1] presumed that it would exist in a colourless state in albinous animals; and this has been proved by Mr Wharton Jones[2] to be the case. The membrane exists in such animals, but the plates are circular rather than hexagonal, and the colouring matter is absent.

In many quadrupeds, a considerable part of the choroid around its vertex, presents a shining and iridescent appearance, which it derives from the addition of a peculiar structure, generally of a gilt green or bluish colour, called the *tapetum*. The portion of the pigmentous membrane which covers the tapetum is colourless, and, when examined with the microscope, its corpuscles are seen to be smaller than those of the rest of

the membrane, less regularly hexagonal, and more separated from each other.

The pigmentum nigrum is not deposited in the pigmentous membrane only, but partly in the substance of the choroid. This is very evident when we scrape away the tapetum, from the internal surface of the choroid of a sheep. The choroid is then seen to be of a black colour. If there is no pigmentum nigrum present on the external surface of the choroid during life, it certainly transudes upon that surface soon after death.

Nothing like vascularity is detected in the pigmentous membrane. It appears to consist of a peculiar structure, with colouring matter imbedded in it, the latter being formed of solid particles about $\frac{1}{15000}$ inch in diameter. Like the rete Malpighianum, the pigmentous membrane is dark and thick in some parts of its extent, pale and fragile in others. The circumstance that both it and the rete Malpighianum are destitute of colour in the albino, confirms the notion that there is an analogy between them. Both are in contact, too, with very vascular structures; the one with the corion and the other with the choroid. Breschet[3] supposes he has discovered a set of glands, near the internal surface of the corion, secreting the mucus, out of which is formed the rete Malpighianum; while to another organ, surrounding the bases of the papillæ of the corion, he attributes the office of furnishing colouring matter to the same part. Glands have been supposed by some to exist, also, in the choroid, for the formation of the pigmentum nigrum; while by others, its secretion has been referred to a villous structure, on the internal surface of that membrane; but nothing positive is known on this head.

Darkest and most abundant in childhood, the colouring matter of the pigmentum nigrum is gradually lost as age advances.

The pigmentum nigrum is insoluble in hot or cold water, and also in dilute acids. It is soluble in caustic alkali; and is precipitated, of a pale brown colour, on the addition of an acid. It is bleached by chlorine. It burns more like a vegetable than an animal substance, and leaves the same ferrugi-

nous ash as the colouring matter of the blood. The iron it contains is too small to produce its dark colour. Neither does this depend on the presence of carbon. Apjohn[4] regards the pigmentum nigrum as an animal substance *sui generis*. Gmelin has pointed out its chemical similarity to the black fluid of the cuttle-fish.

§ 117. *Baptista Porta's notions of the eye. Retina transparent. Absorption of the light which traverses the retina. Opacity of the iris. Eye of the albino.*

There is nothing more instructive, in the history of man, than to go back to the origin of those discoveries, to which the mind has been led by chance or by reflection; and to follow carefully the slow steps of improvement by which philosophy has advanced.

Most of the ancients believed, that vision was accomplished by means of rays issuing from the eye towards the objects of perception.[5] Alhazen and Vitello rejected this opinion; while, by his invention of the camera obscura, and the comparison which he instituted between that contrivance and the eye, Baptista Porta[6] contributed greatly to the adoption of true notions regarding the function of sight. Having completely darkened his room, he bored a hole in one of the window-shutters, and at the opposite side of the room received the rays upon a concave mirror, by which being reflected, they formed a distinct inverted image of remote objects, and an indistinct erect one of those which were near. Struck by the analogy of this experiment to the phenomena of vision, he compared the pupil to the hole in his window-shutter, and supposed that the interior surface of the eye, by reflecting the light forward to the middle of the organ, there effected the production of sight. While he thus explained correctly the office of the pupil, he fell into two mistakes regarding the destination of the light which it transmits; for, *first*, the rays, at least those from distant objects, striking the interior concave surface of the eye, if reflected, would not meet in the centre of the eye, but in the focus of the reflecting surface, that is to say, at a

distance from the retina, of half the radius of the retina's concavity; and, *secondly*, such reflection is prevented by the pigmentum nigrum. Vision is not effected as Baptista Porta supposed, in the centre of the eye, but as Kepler afterwards discovered, at the retina itself.

Mery[7] showed that the retina, during life, is transparent like water. The rays of light, converging to foci by means of the refractive powers of the cornea and humours, strike the retina, and produce a peculiar impression upon that nervous membrane, not by impulsion, but in some other way which we do not understand. Having done so, they are immediately absorbed by the pigmentum nigrum, which thus prevents the confusion in vision which would necessarily result, were the rays permitted to be reflected from one part of the interior of the eye to another. This, then, is the function of that portion of the pigment which lies between the retina and the choroid. It is similar to the office performed by the black coating of the inside of the tube of a telescope or microscope. As to the pigment so abundantly deposited on the posterior surface of the iris, and on the corpus ciliare, its chief use is to render these parts perfectly opaque, so that no light may be transmitted through them.

In the natural state of the human choroid, there is little or no observable reflection of the light which has entered the pupil. In one instance, Sir David Brewster saw a reflection of a bright red colour, with a purplish tinge, from the bottom of the eye of a boy about ten years of age. In a girl, at the Glasgow Eye Infirmary, I noticed also a purple reflection.

In old age, when the pigmentum nigrum becomes very pale, there must be more or less reflection; but the glaucomatous state of the crystalline, which accompanies this change in the choroid, prevents us from observing the reflection distinctly.

The iris of the albino is semitransparent, from want of the colouring matter of the pigmentous membrane, and as this membrane, where it lines the choroid, is equally colourless, vision is dazzled by the influx of ordinary daylight, and fatigued by its reflection from the whole of the interior surface of the eyeball. Hence the albino's impatience of light, perpet-

ual nictitation, and indistinctness of vision. His eyes are also affected with constant and uncontrollable oscillation, which continues even when he is in the dark and his eyeballs shut. His iris is generally of pale bluish-red colour, and through the pupil there is an evident red reflection from the blood circulating in the choroid. The pupil is lively. The sight is myopic.[8]

§ 118. *Reflection of light from the tapetum of some of the lower animals.*

The eyes of the cat are said to shine in the dark; and the same is observed of the dog, sheep, ox, horse, and various other animals. The light is not phosphoric, as some have imagined, but is simply a reflection from the membrane, called, from its resemblance to a piece of velvet, the *tapetum* (§ 116), which exists in those animals on the concave surface of the choroid, but is wanting in man, and the ape-tribe, in hogs, the rodentia, and birds.

Prévost[9] has shown that the less extraneous light the eye of the observer receives, the more sensible it is to that reflected from the tapetum. In a long and narrow passage, closed on all sides excepting the entrance, by which, during a very dark night, there could enter but little light, he saw the eyes of a cat shining. They projected strongly upon the dark ground of a sort of deep niche, which made them appear like burning coals. The light received by the eyes of the cat, and which they reflected, was very weak in this case; but to balance this, the eyes of the observer not being affected by any other light, were necessarily very sensible to it. On another occasion, being in a room where the sun shone, Prévost looked at the eyes of a cat whose head was turned towards one of the corners of the room, in such a direction that he himself received neither the direct rays of the sun, nor the sun-light directly reflected. Here the eye of the cat received much more light than in the other case, and transmitted more to the observer, but his eyes receiving more light from another source, and being on this account less sensible to the light coming

from the tapetum, the eyes of the cat did not appear so luminous.

The eyes of a cat do not shine in absolute darkness. Prévost remained for thirty or forty minutes at a time, in dark places, with cats, without their eyes manifesting any luminousness; although, an instant before or after, their eyes shone as usual, when they were suitably exposed to a certain degree of light.

The animals whose tapetum reflects the light do not lose this property with life, which shows that the reflection is not connected, as some naturalists have supposed, with the passions by which the animal is affected. The animals whose eyes shine most, are often very tranquil at the moment when the phenomenon is most striking. The appearance can also be imitated, with all its peculiarities, by placing bits of tinsel in suitable circumstances.

Dr Drummond[10] of Belfast first observed that the tapetum, on being dried, becomes black, and loses entirely the power of reflecting its green or blue tints, till it is again softened in water. Even after twenty years' desiccation, the tapetum of an ox's eye, as black as charcoal, is revived in all its original brightness, by immersion in water.

It is also a curious circumstance in the colours thus produced, that although they are apparently those of thin plates or fine filaments, and therefore appear different in different positions,[11] they advance immediately from black to blue and green of the second order, all the intermediate colours of the first order being omitted. The same phenomenon occurs in the peacock's tail, in the plumage of birds, and in Labrador feldspar. No satisfactory explanation has been offered of this remarkable interruption of continuity.

The purpose served by the reflection of light by the tapetum is not understood. Reasoning *à priori*, we should say it would render the eyes weak and impatient of light. The vulgar opinion is that it serves as a light to the animals and assists them in seeing in obscurity; but it is not the light which proceeds from the eye to an object, which enables the eye to perceive that object, but the light which arrives in the eye from

without. In absolute darkness, there is no issue of light from the tapetum. Nocturnal birds see very well in light with which the human eye can distinguish no object, but as they have no tapetum, the acuteness of their vision must be ascribed to the great dilatability of their pupil, and the extreme sensibility of their retina. The notion that the rays of light, reflected from the tapetum of other animals, by impressing the retina a second time, thereby increases the power of vision, is therefore not likely to be just.

Prévost remarks, that the animals whose eyes shine in obscure light, are all of the number of those whose motions the night rather favours than impedes. He considers the action of light on the retina to be chemical, and that its sensibility to light being therefore susceptible of a sort of saturation, it was necessary, in order to let it have all the delicacy which it would require to serve the animal during the night, either to take care that the eye should receive very little light during the day, or that this light, at least what was superabundant of it, should be immediately sent off by a reflector, which would prevent it from entering into combination. Hence, he thinks, the contracted pupil of the cat during the day, and the reflection from its tapetum.

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[1] Dissertatio sistens Indagationem Chemicam Pigmenti Nigri, 67; Goettingae 1812.

[2] Edinburgh Medical and Surgical Journal, xl. 81; Edinburgh 1833.

[3] Annales des Sciences Naturelles, Seconde série, ii. 321; Paris 1834.

[4] Cyclopædia of Anatomy and Physiology, ii. 181; London 1837.

[5] A witty old poet thus declares his adherence to the Platonic doctrine :—

It must be questioned in philosophy,
Whether the sight thats resiant in the eye,
Be first by sending out those radiant streames,
Or els by taking in reflexed beames.
Might I, with my poore skill, resolve the doubt,
I should determine 'twere by sending out.
So nimbly doe we others faults discrie,
So blinde we are when we looke inwardly.

JOHN HEATH. 1610.

[6] Magiæ Naturalis Libri iv. fol. 119; Antverpiæ 1560.

[7] Memoires de l' Académie Royale des Sciences pour 1704, 265.

[8] See a minute and interesting account of albinism in Dr Sachs's work, entitled Historia Naturalis duorum Leucacthiopum, auctoris ipsius et sororis ejus. Solisbaci 1812.

[9] Edinburgh New Philosophical Journal, January 1827, 297.

[10] Edinburgh Encyclopædia, xv. 623; Edinburgh 1830.

[11] Newton's Opticks, Book ii. part iii. prop. 5.

CHAPTER XV.

FUNCTIONS OF THE RETINA AND OPTIC NERVE.

§ 119. *Primitive nervous fibres. Structure of the chiasma. Jacob's membrane. Nervous and vascular layers of the retina. Entrance of the optic nerve. Transparent point in the vertex of the retina. Microscopical structure of the retina. Size of its papillæ.*

It is generally admitted, that the varicose or jointed appearance, described by Ehrenberg, in the primitive nervous fibres, or tubules, of which the retina, the optic nerve, the brain, and other parts of the nervous system are composed, is the effect of compression or commencing decomposition. To the naked eye, the optic nerves, from the tubercula quadrigemina to the chiasma, or junction of the right nerve with the left, present a pulpy appearance; but examined microscopically, with the necessary precautions, they are found to consist of primitive nervous fibres, of extreme tenuity, running side by side. It is only anteriorly to the chiasma, that the optic nerves become invested with their proper neurilema, which is a condensed cellular sheath, surrounding the nerve exteriorly, and dividing it interiorly into numerous fasciculi or nervous fibres.

To see the interior structure of the chiasma, it should be steeped in concentrated muriatic acid for twenty-four hours, and a horizontal section made of it with a thin sharp knife. The appearance then presented to the naked eye, by the fibres in the chiasma, is represented by Müller.[1] The connexion be-

tween the fibres of the two nerves is sufficiently distinct, but does not partake much of a decussation. No fibres are seen in the mesial portion of either nerve going to the chiasma. The fibres farthest from the axis of the chiasma continue their course from the right root of the chiasma towards the right eye, and from its left root towards the left eye. Those near the axis form, towards the posterior edge of the chiasma, a plexus or net-work; those towards its anterior edge are connected by loops, or commissural arches, running from the one nerve to the other. A nearer approach to a semi-decussation is seen in some quadrupeds; for example, in the horse. The chiasma of amphibia, reptiles, and birds, has an internal laminated structure; the laminæ of the right nerve passing between those of the left, like the crossed fingers of our two hands. In the ray, and other cartilaginous fishes, the nerves are closely connected by a commissure, but do not decussate. In osseous fishes, the two nerves are connected soon after their origin by a slender transverse commissure, and then decussate, without forming any chiasma.

If one of the fasciculi of the optic nerve be examined with the microscope, it is found to consist of primitive nervous fibres. On the nerve (8, fig. 3) reaching the sclerotica, the sheaths of the fasciculi cease, and hence the nerve is considerably contracted in diameter, immediately before it expands into the retina, (4, fig. 3). The centre of the nerve is occupied by the central artery and vein.

The retina is commonly described as consisting of three layers. The external is Jacob's membrane, which is placed in contact with the pigmentous membrane (§ 116). It is exceedingly thin, and floats away from the other layers when the eye is dissected in water; what remains is properly the retina, consisting of medullary or nervous substance, and of the blood-vessels by which the nervous substance is nourished. We cannot separate what is called the medullary or nervous layer from what is called the cellulo-vascular layer by dissection: but if we allow the former to dissolve, it leaves the blood-vessels at least of the latter spread out over the vitreous body.

The optic nerve does not enter the eyeball in the line of its axis, but about $\frac{1}{5}$ inch to the nasal side of the axis. After death, the retina loses its natural transparency, and on being exposed to the air, or touched with any fluid, it becomes more or less white and opaque. At its vertex, however, and consequently in the focus of the cornea and humours, it retains its transparency, being there considerably thinner than in the rest of its extent. This transparent spot, about $\frac{1}{60}$ inch in diameter, was discovered by Soemmerring, and considered by him as a *foramen.* It is surrounded by a circular portion of the retina of a yellow colour. Unless perfectly supported by the vitreous body, the retina falls into a fold from the optic nerve towards the temporal side of the eye, so that the transparent spot, with its yellow areola, is apt to escape notice. The membrane of Jacob also obscures this part of the retina.

If we take the eye of a white rabbit, clean it completely of muscular and cellular substance, and hold its cornea towards the sunbeams or a lighted candle, we see distinctly, through the sclerotica and choroid at the back of the eye, the fasciculi of the optic nerve radiating through the retina. A similar mode of distribution probably exists in the eyes of all other animals.

Ehrenberg first discovered in the retina primitive nervous fibres. According to him, the retina is a cerebral substance, formed chiefly by an expansion of the optic nerve, covered and penetrated by a close vascular net-work. On the internal surface of the retina of some animals, he discovered papillæ.

The microscopical anatomy of the retina has been elucidated chiefly by Treviranus.[2] He states, that, after the optic nerve has penetrated through the sclerotica and choroid, the nervous fibres spread themselves out, either singly or in fasciculi, on the convex surface of the retina, in all directions. Each individual fibre, or each fasciculus of fibres, at a certain part of its course bends towards the concave surface of the retina, passing, as it does so, through two vascular net-works, one formed by the central vein, and a second by the central artery of the retina. From these layers, the fibres receive a sheath, which increases their diameter, and thus invested, they

terminate in papillæ, perpendicular to the concave surface of the retina.

The papillæ, separating soon after death from the nervous fibres of which they are the terminations, and floating in the field of the microscope, have given rise to the notion sometimes entertained that the internal surface of the retina is granular.

Treviranus found the fibres on the external surface of the retina of the sheep to measure scarcely .001 millimetre = .0000394 English inch thick, the papillæ on the internal surface between .001 and .002 millimetre = .0000394 and .0000788 English inch. Whether each papilla is the end of one fibre only, or whether several papillæ are connected with each fibre, is uncertain.

Gottsche[3] describes an external layer of the retina, consisting of round molecules or granules; and a second layer, which is tough, smooth, and fibreless, and serves to support the third layer, consisting of the nervous fibres. He does not regard the blood-vessels as forming a distinct layer.

Valentin, Langenbeck, Michaelis, and others, all vary in their accounts of the microscopical anatomy of the retina. There appears to be no doubt that in addition to the structures described by Treviranus, there is a layer of granules, partly covering the nervous fibres, and partly interposed between them. In the areola surrounding the central spot of the retina, the granules are yellow. The central spot itself is abundantly supplied with primitive nervous fibres; but is destitute of granules and of blood-vessels.

The labours of the microscopical anatomists of the present day confirm, in a remarkable manner, the conjectures in which former physiologists had indulged, respecting the ultimate elementary fabric of the nervous system, and amongst the rest of the retina. "The optic nerve is a bundle" says Porterfield,[4] "of very small fibres or threads of a certain determinate bigness. These fibres at one end arise from the brain, and at the other terminate in the retina; upon the anterior surface of which they may be supposed to stand erect, like the pile on velvet." In another part[5] of his writings, he calculates, from the minimum visibile (§ 83), the probable size of

the fibres of the human retina. Thus, if the smallest angle under which an object can be seen is 1′, and this object is supposed to affect one fibre only of the retina, then the diameter of the fibre will be $\frac{1}{7200}$ inch, which, as far as can be guessed from Treviranus's measurements of the papillæ in various animals, is probably not far from the truth. The diameter of the papillæ of the retina of the sheep is stated by Treviranus to be between .001 and .002 millimetre; of the rabbit .003; of birds from .002 to .004. Now, .003 millimetre = .00012 English inch, and .004 millimetre = .00016 English inch, the mean between which, or, as an approximation, between $\frac{1}{6300}$ and $\frac{1}{9000}$ inch, is equal to $\frac{1}{7650}$ inch.

On the same supposition, of the eye being capable of conveying a distinct idea of two points subtending an angle of 1′, and taking into account the decreasing sensibility of the retina from its vertex in all directions, Dr Young[6] calculated that the retina probably contained about 10 million distinct points, and the optic nerve several millions of distinct fibres.

§ 120. *Circulation in the retina generally invisible. Experiments producing a spectrum of the blood-globules and blood-vessels.*

1. Among the innumerable particulars, in the structure and functions of the eye, calculated to excite our wonder and admiration, there is perhaps none more remarkable than the fact, that the pressure of the blood, moving through the retina, produces, in the ordinary exercise of vision, no sensible impression. The circulation of the globules, however, becomes evident to most persons, when they look steadily for some minutes through a window at the sky. They then begin to perceive very numerous lucid points, careering, as it were, in various directions over the surface of the window-glass. The appearance is readily distinguished from the morbid sensations called *muscæ volitantes;* and the resemblance of the rapid and revolving course of the spectra to that of the globules of the blood, as seen in different parts of a living animal under the microscope, leads us without hesitation to refer it to an impression made on the retina by the blood, circulating in its vessels.

2. Purkinje[7] pointed out, that, by a variety of methods, a spectrum might be produced of the blood-vessels of the retina. This may be done, for instance, by moving, in a room otherwise dark, a lighted candle slowly and in different directions, transversely or circularly, some inches before one or both eyes. By and by, a spectrum is seen, in which, proceeding from the vicinity of each optic nerve, two trunks appear bending their course upward and outward, and two downward and outward, while two others run inward, all of them giving rise to numerous branches. The appearance continues only so long as the light is in motion.

Two other methods are described by Purkinje,[8] in which the experiment may be performed. The one consists in moving rapidly, and in a sort of tremulous way, before the eye directed towards the clear sky, a black card with a hole in it, one line in diameter. An extremely complicated net-work of blood-vessels appears of a grayish white colour, in which the ramifications of the upper trunks are seen to anastomose with those of the lower. If the diameter of a line allows too much light to pass, a smaller hole should be tried.

The third method is to take a lens, of about an inch focus, place one's-self in clear sunshine, and throw the focus through the sclerotica at the outer side of the eyeball into its interior, moving it at the same time tremulously hither and thither. The entrance of the optic nerve now appears as a bluish ellipse, from whence divaricate the blood-vessels in the manner already mentioned, and exactly as Soemmerring[9] figured them in his paper on the *foramen centrale*, and as Mariotte[10] had figured them a hundred and twenty years before. The distinctness of the appearance is increased, by holding a sheet of black paper before the face. Purkinje says, that this experiment is much more easy than that with the lighted candle, and not in the least injurious to the eye, the light being much moderated by passing through the sclerotica and choroid.

In none of the methods of performing this experiment, is the motion of the blood through the vessels perceptible.

In the first method, Purkinje states that the spectrum appears dark. With me, it has always appeared grayish

white. It is probable, that the dark or light appearance of the spectrum will depend on the intensity of the light employed, exactly as in the production of common ocular spectra; for, in this case, if the light is intense, the spectrum resembles the object in the distribution of the light, but if it is not intense, the spectrum is generally dark at those places where the object is light, and light at those places where the object is dark.

In the above experiments, those parts of the retina where are the trunks of the blood-vessels, will be less excited by the light than the rest of the retina, and the result serves to show that in vision we perceive merely certain states of that membrane.

§ 121. *Retinal images. They are merely a concomitant of vision. Area of retina. Is it all equally sensible? Perfect vision effected only in the optic axis. Use of the straight muscles. Duration of impressions on the retina. Comparetti's hypothesis. Experiment illustrative of oblique vision. Extent of oblique vision.*

When we move a lighted taper before the eye, upward, downward, to the right or to the left, the minute inverted image of the taper travels in a contrary direction across the whole area of the retina, from its lower to its upper, and from its nasal to its temporal, margin. On other occasions, the entire field of the retina is crowded with the images of objects occupying almost an entire hemisphere, as when we regard from a height an extensive landscape, crowded with men and animals, houses and trees, rivers and mountains, the ocean and the sky.

The student should convince himself of the truth of these statements, by taking the eye of a white rabbit, and observing the various situations assumed on its retina by the image of a single luminous object, such as a lighted taper, moved in various directions, a few inches before the cornea. He should then place the eye in a hole, exactly fitting it, in a window-shutter, with the cornea directed towards the street, when he will observe, especially if the sun is shining, the

whole back of the eye pictured over with the images of the houses, and of the men and other moving objects in the street.

Similar images to those observed in these experiments are formed on the living retina. It is scarcely necessary to state that they serve in no way to produce perception, but are merely an invariable and necessary concomitant of vision. It is the impression made by the light on the retina which is the means of perception, and not the image.

The retina forms a cup, the area of which is to the area of the sphere of which it is a segment as 9 to 16. The question naturally suggests itself, Is the whole of this area equally sensible to light, equally fitted to receive impressions, and to convey them to the optic nerve?

Whether the retina is in itself all equally sensible, is a question on which we do not possess sufficient facts to enable us to decide. That in connexion with the cornea and humours, by which the rays reaching the eye are concentrated to foci on the retina, its vertex only can receive a perfect impression, while the impressions on every other part of it must be imperfect, is easily understood. The fact is, that though we receive a general impression from a whole hemisphere of external objects, we find, when we come to examine any thing minutely, that our power of perfect vision is extremely confined. On looking, in a general way, at the page of a printed book, we might suppose we saw distinctly every letter in it, but when we come to view it closely, we find that we can read, for instance, only one line at a time, that we can make out that line only word by word, and that if we examine the form of any single letter, the other letters appear indistinct.

If we hold our finger at the distance of 10 or 12 inches straight before us, we see it perfectly, both because it is placed at such a distance that the rays reflected by it are brought to focal points on the retina, and because being in the optic axis (§ 54), its image falls on the vertex of the retina. If, keeping the eye steadily directed forward, we move the finger to one side, it soon begins to become less distinct; and though we still see it, even when it is so much to one side as to form an angle of more than 90° with the axis of the eye, so that its image

must fall near the anterior margin of the retina, the perception we have of it in this situation is very indistinct, so much so that were such an object presented to us in that position by another person, we should scarcely be able to tell what it was.

However great the pains bestowed by nature to render the eye aplanatic (§ 65), it must, like every other optical instrument, converge most truly the rays which are nearest its axis; and it is on account of this circumstance, that the eye is so extremely moveable, being supplied with the four straight muscles, which direct its axis, with instantaneous rapidity, towards the objects which we wish to see distinctly. We turn towards every object the centre of the pupil, not from habit merely, but because this direction of the eye enables us to avoid the aberration of pencils falling obliquely on the cornea, and therefore to perceive the object with every possible advantage.

It is familiarly known, that the effect of light on the retina continues for a time. Hence it is, that though we close our eyes about ten times in every minute, we do so without perceiving that we are in the dark, or losing sight of the objects around us. For the same reason if a burning stick be whirled round in the dark with a sufficient velocity, the whole circle which it describes appears luminous, showing that the impression made by the light on the retina, when the stick is in any one point of the circle, remains till the stick returns to the same point. Newton supposed the impression of light on the retina to continue about one second of time. Others calculate the duration of the after-impression, to be only about $\frac{1}{3}$d of a second. It depends undoubtedly on the intensity and duration of the primitive impression. Comparetti, believing that the retina is not equally sensible in all its extent, but that only a certain portion of it, near the axis of the eye, is capable of conveying distinct impressions of minute objects, supposed that distinct vision is effected by the vertex of the retina being moved most rapidly towards every point of the object; and that what is seen apparently out of the axis of the eye, is caused by the duration of the first impression in the axis.

It is evident, that such a motion of the eye as Comparetti

describes, does not take place in our ordinary manner of regarding large objects, although something very like it is employed when we view their parts in detail, or examine small objects minutely.

A simple experiment suffices to show, both that the lateral parts of the retina possess a very considerable degree of sensibility, and that we sometimes see objects by means of oblique vision, when the circumstances in which we are placed would prevent direct vision.

If, with my right eye, the left being shut, I look at a lighted candle, placed a little to my right, and bring my open hand into such a position by the side of my head that its edge just hides the candle from my view, I only require to direct my eye towards the left, to bring the candle into view. When I do so, the image evidently falls on the nasal side of the retina. When I again turn my eye towards the candle, it is no longer visible, the rays which should pass through the pupil being arrested by the hand. This explains the optical paradox, that we sometimes see an object we do not look at, and cannot see this same object when our eyes are turned towards it.

Dr Young remarks, that the visual axis being fixed in any direction, he could see a luminous object placed laterally at a considerable distance from it; but that the angle was different in different directions. Upward it extended to 50°, inward to 60°, downward to 70°, and outward to 90°. He observes that these internal limits of the field of view nearly correspond with the external limits formed by the different parts of the face, when the eye is directed forward and somewhat downward, which is its most natural position.

The whole extent of perfect vision Dr Young estimates at "little more than 10°." He then corrects himself, and says that the imperfection begins within a degree or two of the visual axis, of which there can be no doubt. He mentions that the motion of the eye has a range of about 55° in every direction; so that the field of perfect vision, in succession, is by this motion extended to 110°. His statements, that at the distance of 5 or 6 degrees from the axis, the imperfection be-

comes stationary, until, at a still greater distance, vision is wholly extinguished, and that the imperfection, although partly owing to the unavoidable aberration of oblique rays, is principally caused by an insensibility of the retina, cannot be received without some more conclusive proofs than any which he has advanced in their support. I know of no fact which would lead us to believe that the retina is insensible, even where it is most remote from the axis of the eye; and although it is probable that its sensibility is most exquisite at its vertex, where it is thinnest and devoid of blood-vessels, the gradually increasing imperfection of vision, as the image approaches the margin of the retina, receives a very satisfactory explanation in the feebleness with which the membrane must be impressed, by rays thrown upon it with greater and greater obliquity.

§ 122. *Mariotte discovers the extremity of the optic nerve to be insensible to light.*

Mariotte,[11] having observed that the end of the optic nerve within the eye corresponds, neither in man nor in the lower animals, to the axis of the eye, where the image is formed of objects seen directly, but that it is placed in the human eye a little upward, and towards the nose, felt a desire to know whether vision was more or less distinct when the image fell on the nerve. To ascertain this, he had recourse to the following experiment. He fastened on a wall, about the height of his eyes, a small round piece of white paper, to serve him for a fixed point of vision, and then another piece of paper towards his right, at the distance of about two feet from the former, but a little lower, in order that it might strike his right optic nerve. Placing himself opposite to the first paper, and withdrawing from it gradually, with his right eye fixed upon it, and his left eye shut, when he came to the distance of about nine feet, the second paper, which was nearly four inches in diameter, entirely disappeared. He could not attribute this to the obliquity of the object, in as much as he continued to see other objects, placed still more to the right; so that he could have believed that the paper had been removed,

if he had not found it again, on moving his eye cver so little. But no sooner did he regard steadily his first paper, than the other which was to the right, instantly disappearcd; and to see it again, without moving his eye, he found it neeessary to shift his placc.

Mariotte repeated this experiment frequently, varying his distance, and separating or approximating thc papers proportionally. He performed it with his left eye, keeping the right shut, after having placed the paper to the left of his point of view, so that from the situation of the parts of the eye, there eould be no doubt that the deficicncy of vision took place when the image fell on the optic nerve. He mentions as a surprising cireumstance, that when one loses sight in this way of a circular piece of black papcr, placed on a white ground, no shadow or obseurity is perceived in the situation of the black paper; but the whole wall appears white.

On making others repeat his experiment, Mariotte found that some lost sight of a piece of paper eight inches in diameter at the distanee above mentioned, while othcrs requircd the paper to be a little less. This he attributes to the different size of the optic ncrve in different eyes.

From his experiment, Mariotte drew a very unfortunate conclusion; namely, that the choroid, and not the retina, was the organ of vision. If vision took plaee in the retina, then it should exist, he argued, wherever the retina is. But the rctina covers the optic nerve, and yet this part is destitute of the power of vision. If this powcr resides in the choroid, the reason is plain why the optic nerve cannot enjoy it, for the choroid surrounds the nerve, but does not cover it, as it does the rest of the bottom of the eyc.

These views of Mariottc wcrc rcfutcd by Peequet and Perrault; the former of whom suggested that the disappcarance of the object, in Mariotte's expcriment, might be owing to the trunk of the artery and vein in the ccntre of the optic nerve.

To be convinced of thc truth of Mariotte's diseovery, it is unnccessary to use objeets of sueh a size, or to view them at so great a distance, as he did. Two small black wafcrs, laid upon a shcet of white paper, answer very well; but the experiment

is more striking, when three wafers are placed in a horizontal line, at the distance of about three inches from one another. If the student closes his right eye, and places his left eye directly over the right-hand wafer, at the distance of 5 or 6 inches, he will see all the three wafers, but on gradually withdrawing his eye to the distance of 11 or 12 inches, the middle wafer will vanish, and the colour of the paper will appear in its place. The left-hand wafer, though its image must fall more obliquely on the retina than that of the middle wafer, continues in view. The middle wafer will reappear, on again bringing the eye a little nearer, or withdrawing it a little further. The same effect will be produced if the left eye is closed, and the left-hand wafer regarded with the right eye.

When the middle wafer disappears, it is about 15° to the right or to the left of the wafer upon which the right or the left eye is fixed, or, in other words, to the right or left of the optic axis. The distance from the eye of the object which disappears, is a little less than four times its distance from the point on which the eye is fixed.

If candles or other highly luminous bodies are used instead of wafers, the body to which the eye is not directed does not wholly disappear, but without leaving any distinct impression of its form, produces the sensation of a faint cloudy light.

As the whole secret of Mariotte's experiment consists in making the image of an object fall exactly upon the end of the optic nerve, Picard and Porterfield[12] devised means by which the experiment might be performed with both eyes open.

Porterfield's method is to fix upon the wall two circles of paper, at the same height, and about three feet from each other. The observer places himself directly opposite at the distance of twelve or thirteen feet, holds his finger about eight inches before his eyes, so that it may cover from his right eye the left-hand paper, and from his left eye the right-hand paper. If he now looks attentively to his finger with both eyes, he loses sight of both papers. This proceeds from the direction of the eyes, and the situation of the finger; for each of the eyes now receives the image of the object on its own side

upon the end of the optic nerve, while the finger covers the eye from the object on the other side. The experiment will not succeed, if the eyes are very unequal in their focal distance.

We are not sensible, in the ordinary exercise of vision, of any defect from the existence of an insensible spot or *punctum cæcum* in each eye, when both our eyes are open, because, as Bernoulli[13] observes, it is impossible that any object, or part of an object, can be so situated, as to form its image to the inside of the optic axis in both eyes; and therefore what is lost to one eye, is always visible to the other.

We are not only insensible of any defect in our sight when both eyes are open; but, in looking at objects of a uniform colour with one eye, the other being shut, we see no dark spot, answering to the punctum cæcum. This is evident, when the objects used in the experiment, are white wafers on a black ground, or *vice versa.* The white or black wafer absolutely vanishes, and the space which it covers appears to be completely black, or white, as the case may be. The explanation offered of this fact, is, that though the optic nerve is insensible to light falling directly on it, yet it is susceptible of receiving luminous impressions from the retina around it; the consequence of which is, that when the wafer disappears, the spot which it occupied, in place of appearing black, has always the same colour as the ground upon which the wafer is laid, being white when the wafer is placed upon a white ground, and black when the wafer is placed upon a black ground.

To ascertain the precise situation of the punctum cæcum in reference to the optic axis, its extent, and the effects of different degrees of light on its apparent extent, have been the subjects of repeated inquiry.

Porterfield[14] calculates the matter thus:—In Mariotte's experiment, most observers lose sight of an entire circle of white paper, whose diameter is about the ninth or tenth part of its distance from the eye. As the triangle, whose base is the diameter of this circle, and vertex the optical centre of the eye, is similar to the triangle whose base is the diameter of the image of that circle on the retina, and vertex the same

centre, where the extreme rays are supposed to intersect each other; it follows, that the diameter of the image will also be about the ninth or tenth part of its distance from the optical centre of the eye. This distance is about six lines, the ninth part of which is $\frac{2}{3}$ line, which answers pretty exactly to the diameter of the optic nerve.

To find the place of the entrance of the optic nerve, Dr Young[15] adopted the following plan. He fixed two candles at ten inches distance, retired sixteen feet, and directed his eye to a point four feet to the right or left of the middle of the space between them. They were then lost in a confused spot of light; but any inclination of the eye brought one or other of them into the field of view. In Bernoulli's eye, a greater deviation was required for the direction of the axis; and the obscure part appeared to be of greater extent. He regarded[16] it as equal to a seventh of the diameter of the eyeball. Dr Young, from the experiment above related, concluded the distance of the centre of the optic nerve from the visual axis to be $\frac{16}{100}$ inch; and the diameter of the most insensible part of the retina, $\frac{1}{30}$ inch. In order to ascertain the distance of the optic nerve from the point opposite to the pupil, he took the sclerotica of the human eye, divided it into segments, from the centre of the cornea towards the optic nerve, and extended it on a plane. He then measured the longest and shortest distances from the cornea to the perforation made by the nerve, and their difference was exactly $\frac{1}{5}$ inch. To this he adds $\frac{1}{50}$, on account of the eccentricity of the pupil in the iris, making the distance of the centre of the nerve from the point opposite the pupil $\frac{11}{100}$. Hence he concludes, that the visual axis is $\frac{5}{100}$, or $\frac{1}{20}$ inch, further from the optic nerve than the point opposite the pupil; adding, that it is possible, that this distance may be different in different eyes.

Dr D. Griffin has published[17] some careful experiments, undertaken for the purpose of determining the situation and size of the punctum cæcum.

The back of his head being placed against one wall of an apartment, the distance was measured from the centre of his eye to the opposite wall, where hung a convex mirror, in the

centre of which he could view the reflected image of a candle. His left eye being shut, he viewed the reflected image with his right. Then as he gradually directed his eye towards the left, a wafer was placed on the wall at the last point at which he was sure he could still see the image, a second at the first point where he was sure he could not see it, a third at the last point where he was sure he could not see it, and a fourth at the first point where he was sure he could see it. A line drawn from half the distance between the first and second wafers to half the distance between the third and fourth, represented the angular breadth of the insensible spot; and, accordingly, when the right eye was directed to the middle point of this line, the image of the candle was perfectly invisible, from its falling on the centre of the punctum cæcum. Moving the eye upward and downward from the middle of this line, the vertical diameter of the punctum cæcum was obtained. In the same manner, it was easy to ascertain the angular distance of the centre of the punctum cæcum from the reflected image, and consequently the distance between the centre of the punctum cæcum and the optic axis. From an average of several observations thus made, Dr Griffin found, that, for his right eye, the mean distance of the centre of the punctum cæcum from the optic axis was 15° 26′, and for his left eye 15° 43′.

Dr Griffin varied his experiments, by using as objects two unshaded candles, in Dr Young's method; by substituting for the image reflected from the mirror, the flame of a candle shaded by a cylinder of dark paper, in which a small hole was cut, through which the light might appear; and, lastly, by placing a circular piece of paper, seven or eight inches in diameter, on a light-coloured wall, and receding till it was barely but completely hidden. He found that with the circular piece of paper on a light-coloured wall, the light being feeble and the contrast slight, the diameter of the punctum cæcum appeared to be 7° 31′; with the image reflected from the mirror, in which more than half the light was dispersed and lost, 7° 5′; with the direct light of a candle, seen through a small aperture, 6° 12′; with unshaded candles, 3° 15′. The apparent diameter of the punctum cæcum diminishes, there-

fore, as the strength of the light increases. Hence Dr Griffin concludes that the cause of the blindness is not owing, as Pecquet and others have supposed, to the presence of the central vessels, but to the thickness of the nervous matter, the optic nerve not being yet spread out into those fine filaments which form the retina. He observes, that, at some distance from the centre of the optic nerve, its sensibility seems dull to moderate lights, and that it is capable at the centre of being roused only by very strong lights. He thinks a small point of light, of exceeding intensity, would assign a very small diameter to the insensible portion of the nerve, if it was capable of discovering it at all. He found the presence of the artery in the centre of the nerve quite perceptible by a reddish glare, which showed itself about the middle of the invisible part of the field; but this appearance took place only in the experiment with unshaded candles.

There is no doubt that the punctum cæcum is situated a little higher than the extremity of the optic axis. It is evident, however, that no complete proof of this can be obtained, except from experiments performed with both eyes at the same time, since there is otherwise nothing to assure us that the head is not placed obliquely during the experiment. Dr Griffin's experiments on this point gave 1° 11′, as the elevation of the centre of the optic nerve above the plane passing through both optic axes.

§ 123. *Line of visible direction. Apparent place of an object depends on the part of the retina impressed, and not on the direction of the incident rays. Porterfield's law of visible direction. Objections to it.*

It is a fact, universally admitted, that the apparent place of any object depends on the part of the retina impressed by the rays proceeding from the object, whatever be the course in which the rays may reach the retina.

Any point *a* of the image *a b c*, fig. 54, is formed by a multitude of rays lying within the angle L *a* L′, each of which has a different direction from that of the others; and yet

when a similar collection of rays is formed on the retina, the observer sees only one point A, situated nearly in the direction *a* O A, fig. 54, or *a* A, fig. 58. This *line of visible direction* does not coincide with that of the incident rays, for the directions of the incident rays do not coincide with one another. The situation of the focus on the retina depends, no doubt, on the direction of the incident rays, but the line of visible direction depends on the part of the retina which is impressed.

As the pencil of rays by which any point of an object, such as B, fig. 58, is seen, has its greatest breadth at the pupil, whence it converges to a point, *b*, on the retina, it might perhaps be expected, that, by excluding all the rays except a few near the margin of the pupil, the object would seem to shift its place, since in this case we must see it by means of rays, no portion of which points directly from the object towards the part of the retina impressed. Under such circumstances, however, the object is seen as truly in its actual position as if we had admitted the whole pencil.

If we look over the top of a card at the point of an object, whose image may be supposed to be at *b*, till the edge of the card is just about to hide it, or, what is the same thing, if we exclude from the pupil all the rays except the uppermost, we shall find that the point whose image is at *b*, is seen in the same direction as when the whole pencil flowing from B was employed. If we look beneath the card in a similar manner, so as to see the point of the object by the lowermost ray, we shall see it in the same direction. Hence it is manifest that the line of visible direction does not depend on the course of the ray, but on the part of the retina impressed.

In tracing the course of pencils of light through the eye, it will be found that those entering it at angles of 45° and upwards from the axis, do not contain a single ray pointing directly from the object towards the part of the retina impressed; yet it is well known that objects at such angles, though indistinct from other causes, are seen in their true directions.

The facts now stated prove, that obliquity of incidence in

the rays does not effect any apparent change in the place of the object, provided they still fall on the same point of the retina. The following experiment, by Scheiner, shows, that when the point of the retina is changed, the object undergoes an apparent change of place; and in a direction opposite to that in which its image on the retina is made to move.

If a small object, A, such as the head of a pin, be so placed that its distance from the eye is greater, as we shall suppose it to be in fig. 89, or less, as in fig. 90, than that at which it

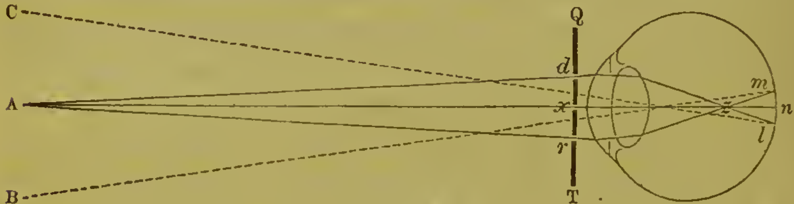

Fig. 89.

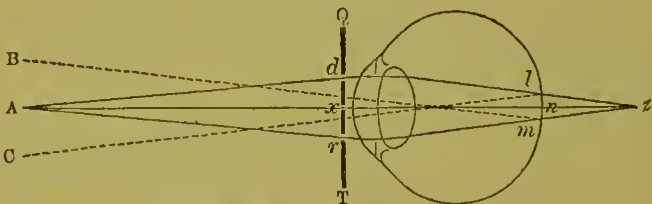

Fig. 90.

would be most distinctly seen with the naked eye, it will appear obscure, because the rays proceeding from it are in neither case brought to a focus on the retina. Close to the eye bring a pin-hole in a card. Let Q T represent the card, and x the pin-hole. The ray of light A x n, falling on the retina at n, will there form a distinct image of the object A, and make it appear in the visual line n x A, which is perpendicular to the retina at the point n. If we now move the card up or down, to the right or to the left, the object will seem to move in an opposite direction. For instance, if the card be moved downward, so that the pin-hole may be at r, the ray of light A r, after passing through the hole, will be refracted in the eye, so as to fall upon the retina, not at n, but at some other point, as m. The object, A, being supposed to be at a greater or less distance than that at which it could be

seen distinctly with the naked eye, all the rays proceeding from it through the pupil must converge to a point, such as *z*, either before the retina, as in fig. 89, or behind it, as in fig. 90; but on the retina itself they must fall at different points, according to the situation of the hole through which they pass; for the eye does not adapt itself to the distance of an object viewed through a perforated card. Now, the object, A, seen through the hole *r*, does not appear in its real place A, but at some other place, as B, in the right line *m* B. If the card be raised, so that the ray A *d* may pass through the pin-hole at *d*, it will fall, after refraction, on the retina at *l*, and the object will appear, not in its real place, A, but at some other place, as C.

If we make two additional pin-holes in the card, so close that all the three, *d*, *x*, *r*, are within the diameter of the pupil, the object, A, will appear at the same time as if in three different places, C, A, B, being multiplied according to the number of holes. This evidently proves, that the rays, flowing from the object through the pin-holes, fall upon different points of the retina. If the object is placed too far from the eye for distinct vision, so that the rays unite at *z*, in front of the retina, and thence diverging strike the retina at *m*, *n*, and *l*, as in fig. 89, on stopping the lower pin-hole, *r*, the lower image, B, will vanish; but if the object is placed too near the eye, so that the rays would unite at *z*, behind the retina, but strike it at *m*, *n*, *l*, before they can come to a focus, on stopping the lower pin-hole, *r*, the upper image, B, will vanish.

If the object, A, be brought to the precise distance from the eye that is necessary for uniting all its rays in a single point of the retina, as *n*, then it will appear single, though viewed through several holes (§ 91). This will be the case, even though the middle hole be closed, so that no rays fall upon the eye but what pass through the holes at *d* and *r*, towards the margin of the pupil; for these rays being united on the retina at *n*, the object will be seen in the visual line *n x* A, though no ray enters the eye in that direction.

It must be an interesting question to determine in what

direction an object will be seen, reckoning from the place where its image falls upon the retina. The simplest and most obvious supposition seems to be, that the visible direction will be in a straight line, drawn from each point of the image on the retina to the corresponding point of the object. A doctrine, however, originally advanced by Kepler,[18] has received the support of Porterfield, Reid, Brewster, Treviranus, and others, that whenever rays, proceeding from any point of an object, are brought to a focus on the retina, the eye perceives that point in the direction of a line perpendicular to the surface of the retina at the point where it is impressed, whatever may have been the direction in which the rays have reached the retina. This assumption has been called the *law of visible direction.* Those who adopt this doctrine, taking it for granted that the retina is a segment of a perfect sphere, assume that its centre forms a *centre of visible direction*, through which a straight line, drawn from the image of any point on the retina, will indicate the direction in which that point will appear to the eye.

In figures 89 and 90, lines are drawn from the points *m*, *n*, *l*, through the focal centre of the eye, which nearly coincides with the centre of curvature of the cornea, to the supposed apparent places of the multiplied object seen through three pin-holes in a card; but agreeably to Porterfield's law of visible direction, the lines should be drawn through the centre of curvature of the retina, which is about $\frac{1}{10}$ inch behind the focal centre. It is worthy of remark, that in announcing this law, Porterfield speaks of it less confidently than those who have followed him, repeatedly stating that every point of an object is seen *nearly* in a straight line perpendicular to the retina at the place of its image. It is plain, however, that a law of this kind can be of no value, unless it be absolute and universal.

The chief proofs offered in support of the law of visible direction above stated, are the following:—

1. Objects, below a certain size, become invisible, when placed about 15° to the right of the optic axis of the right eye, or to the left of the optic axis of the left eye. This de-

fect depends (§ 122) on the entrance of the optic nerve about $\frac{1}{7}$ inch to the left of the axis in the right eye, and at the same distance to the right of the axis in the left. It is presumed, that a right line from the centre of the object to the centre of the optic nerve would strike the latter perpendicularly, and consequently pass through the centre of curvature of the retina.

Harris,[19] in the account which he gives of his own and Mr Short's experiments regarding the punctum cæcum, speaks of such a line as passing through the focal centre of the eye, which is more likely to be the case. He states that the angle contained between the optic axis and a line passing through the focal centre of the eye to the centre of the insensible spot, was in Mr Short's eye about 15° 20′, and in his own about 13° 30′, whereas the angle contained between the optic axis and a line passing through the centre of the retina's concavity to the centre of the insensible spot would be about 25°, which would agree neither with observation nor with the known distance between the extremity of the optic axis and the centre of the optic nerve.

2. If moderate pressure is made with the finger, or a blunt point, on any part of the eyeball lined by the retina, a circular luminous spectrum appears in a direction opposite to the part pressed; and it is asserted, that the spectrum is projected in a line vertical to the point of the retina thus excited to sensation.

The positions of the spectra produced by pressure do not appear to have been ascertained with any degree of accuracy, by those who satisfy themselves with the general fact, that the spectra are opposite to the point compressed. Dr Griffin[20] gives the following as the results of his examinations on this point:—

When the pressure is made on the temporal side of the eyeball, 90° from the axis, the spectrum appears anterior to the bridge of the nose. When the axis is directed towards the nose, and pressure is made as deep as possible on the outside of the eye, the spectrum appears a little within the bridge of the nose. When the axis is directed outward as much as

possible, and pressure is made as deep as one can at the inner canthus, the spectrum stands about 30° on the outside of the point to which the axis is directed. Generally speaking, whatever be the position of the axis when the pressure is made round the ball of the eye and within the edge of the orbit, the spectra appear round the margin of the field of view.

Dr Griffin concludes, that these facts give no support to the notion that the retina has the property of representing objects in lines perpendicular to its surface.

3. Adopting Porterfield's law, Sir David Brewster[21] appears to believe, that the visual stability of objects which occupy the field of vision during the motions of the eye can be accounted for only by supposing that the centre of visible direction, or the point through which all the lines of visible direction pass, is coincident with the centre of motion of the eye. He says, "when we move the eyeball by means of its own muscles through its whole range of 110°, every point of an object within the area of the visible field either of distinct or indistinct vision remains absolutely fixed, and this arises from the immobility of the centre of visible direction, and, consequently, of the lines of visible direction joining that centre and every point in the visible field."

A sufficient objection to this statement seems to be, that objects remain in the same apparent place, even when the head is moved in different directions.

We must now notice some attempts which have been made at a direct refutation of Porterfield's law. They are substantially the same with what has already been stated respecting the angle, under which the eye recognises the effect of the punctum cæcum.

Perpendicular lines drawn from every point of the retina on which an impression is made, towards the object, will nearly coincide with the axis of the pencils of rays which flow from the several points of the object to the eyes, only when the object is placed near to the optic axis. Dr Turner, in the short account he gives of the properties of light in his *Elements of Chemistry*, shows, that were the assumed law true, the

points of objects lying even at moderate distances from the optic axis would appear to the eye at spots very remote from their real position. He thinks it would be more consistent with observation to take the focal centre of the eye considered as a compound lens, as the centre of visible direction.

Dr Griffin[22] contends, that Porterfield's law cannot be true, under the conditions usually specified; viz. that the concave surface on which the retina is expanded is spherical, or nearly so, and that the curvatures of the different media of the eye, and their indices of refraction, as given by the best authorities, do not differ widely from the truth.

Dr Griffin supposes the interior of the eye, on which the retina is spread, to be graduated from 0 to 90°, and so on, beginning from the point where the optic axis strikes that membrane, and marking this point zero. If, employing the usual curvatures and refractive powers of the media of the eye (§ 49, 50), the progress of a pencil of light be traced geometrically, according to the law of the sines, it follows, as Dr Griffin states, that if Porterfield's law is true, the number of degrees marked on the point of the retina where the pencil is found to fall, ought to indicate its degree of inclination to the optic axis before it entered the eye, or, in other words, the direction, in space, of the object whence it came.

Tracing its course, then, in the manner mentioned, a pencil inclined 22° 30′ to the visual axis, as is represented in fig. 91, will fall somewhere about 34° on the retina; one inclined 45°, will fall on a point marked 63°; and a pencil inclined 67° 30′, will fall on a portion of the retina, which, if possessed of the property assumed by Porterfield, must represent the point from whence it came as situated nearly 89° from the axis of vision. Pencils at intermediate stations will

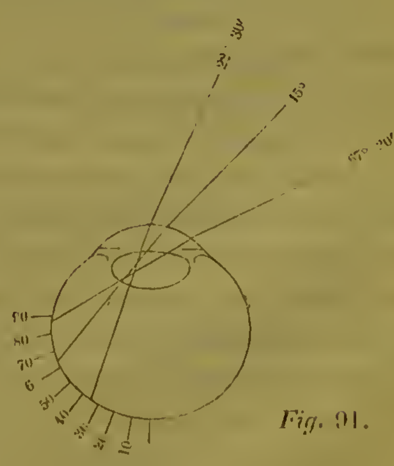

Fig. 91.

be found to deviate in intermediate degrees, but in every case there is an error, which increases with the inclination of the pencil, though not exactly in the same ratio.

It is well known, that when the eye is directed straight forward, we can see objects placed exteriorly at any angle to the optic axis from 0 up to 90°; but it will be found by trials on a diagram such as Dr Griffin describes, while the same rule is followed as for the other rays, that a pencil from an object removed 90° from the axis, cannot possibly be brought to a point marked 90° on the retina. He observes, that we do not get out of the difficulty, by supposing that the indices of refraction of the media have been under-rated; for it is clear, that the refractive power necessary for bringing a pencil which enters the eye at an angle of 45°, or of 70°, to points at the same angular distance from the extremity of the optic axis, would make the eye myopic for pencils near the axis, and would thus render the very best part of the retina useless. Dr Griffin concludes, then, that the law of visible direction, promulgated by Porterfield, has been advanced on a very loose examination of the circumstances, and is not true, nor even nearly true. Without attempting to put the facts which he has stated under any general expression, Dr Griffin rests satisfied with the statement, that when rays of light fall on any point of the retina, that point has the property of representing the object from which they come in its true direction, without any regard to the obliquity of their incidence. This he speaks of as a fact, whereas it is no more than a probable supposition.

Dr Griffin conceives, that the following observations will lead, if not to clearer and more simple, at least to truer notions on the subject of vision, than those usually received.

Rays, forming the same angle with the axis, will always be refracted to the same part of the retina; they will not at one time come to a certain point, and at another be bent more deeply into the eye, but will always strike the membrane at the same distance from the extremity of the optic axis. Considering, therefore, the nervous matter of the retina as made up of numerous zones, distributed in parallel bands, around the point where the optic axis strikes the back of the eye, rays

entering the eye at an angle of 45°, for instance, with the axis, will fall on a zone of nervous matter situated somewhere about 63° from this point. Rays from every object around, situated at that angle from the axis, must fall upon some part of this zone; no rays from objects at other angles can ever touch it; and, according to Dr Griffin, this zone has the property, when rays fall on it, no matter with what obliquity, of representing the object from which they come as standing 45° from the axis. Taking each of the other zones of the retina in the same manner, our perception of the angular distance of every object from the axis is predetermined by the zone of nervous matter on which the rays from the object fall. Under this arrangement, there can be no instability of objects in the field of view during motion, wherever we suppose the centre of motion to be situated, and whatever point the centre of visible direction, if any such there be, may occupy. The conferring on the retina a property of representing all objects in the direction of lines perpendicular to the surface on which the rays impinge, is the only thing, says Dr Griffin, that could endanger their stability during motion of the eye, since, in this case, the coincidence of the centre of visible direction with the centre of motion and centre of curvature, would be absolutely essential to its maintenance, which conditions would be by no means necessary in any other case.

§ 124. *Erect vision with inverted images.*

It is in consequence of the rectilineal progression of light, that the images formed on the retina are inverted (§ 8, 11). The rays which proceed from A, the upper extremity of an object, fig. 58, passing through the pupil and through the lenses of the eye, fall, at *a*, on the lower part of the retina; those from B, the lower extremity of the object, crossing the former, strike the upper part of the retina, at *b;* those from the right side of the object pass to the left side of the retina, those from the left pass to the right, and thus the image is inverted.

In the image on the retina, the relative positions of the parts

of the object remain unchanged, as well as its relations to surrounding objects. The images of all objects, even those of our own bodies, are equally inverted on the retina, and therefore maintain the same relative position. Even the image of our hand, while used in touch, is inverted. Hence, the notion is evidently absurd, that infants at first see objects upside down, and learn to see them in their proper position, by comparing the erroneous information acquired by sight with the accurate information acquired by touch. Many of the lower animals manifest a perception of the true position of objects by means of the sense of sight, from the very first, and before any experience derivable from touch can have had time to operate. To some philosophers, then, there appears no difficulty respecting erect vision, so long as all things equally, and not some objects only, are seen by means of impressions coincident with inverted images.

It is universally admitted, that the impressions on the retina by the rays of light are communicated to the optic nerve, and by the optic nerve conveyed to the brain, the seat of the mind. The mind, in vision, takes cognizance of certain changes in the state of the retina, produced by the influence of different colours; but of the nature of these changes, we know nothing. Whether the differently coloured rays, acting on the retina, cause some peculiar motions of the nervous filaments of which it is composed; or give motion to some subtile fluid contained in those filaments; or effect the retina by a chemical action; we are entirely ignorant. Of this, however, we are certain, that the mind neither views the images on the retina, nor is in any way conscious of their existence. The images, therefore, form merely an inseparable attendant on this function. If there is no image, there is no vision; such as the image on the retina is, such is the appearance of the object, in colour and figure, distinctness or indistinctness, brightness or faintness; yet as the mind never perceives the image, it never judges by it of the object, but by the direct effect which the light, emanating or reflected from the object, produces by touching or traversing the retina.

Kepler's explanation of objects appearing erect, notwith-

standing the inversion of the images on the retina, is, that the mind, perceiving the impulse of a ray on the lower part of the retina, conceives this ray to be directed from a higher part of the object, and perceiving the impulse of a ray on the higher part of the retina, conceives this ray to be directed from the lower part of the object. This view of the matter Des Cartes illustrates, by the supposition of a blind man holding in his hands two sticks crossing each other, with the extremities of which he pushes the top and bottom of an upright object; observing that the man will judge that to be the upper part of the object, which he pushes with the stick held in the lower hand, and that to be the lower part, which he touches with the stick in his upper hand.

This explanation of Kepler has been adopted by Porterfield, Reid, and others, who maintain that the mind, by virtue of a connate immutable law, traces back the sensation from the retina, along right lines drawn perpendicularly from every point of the retina on which the image is formed towards the object itself. Porterfield's law of visible direction, that every point of the object is seen in a right line passing from the image of that point on the retina through the centre of the eye, Reid regards as a law of nature, or law of our constitution, of which law our seeing objects erect, with inverted images, is a necessary consequence.

That the mind perceives by the impulse of a ray of light on the retina, whether the ray comes from above or from below, or that the mind traces back the sensation from the retina to the object, is a mere figure of speech, to which no proper meaning can be attached. Neither the impulse, nor the direction of a ray of light, falling on the retina, can be an object of sense.

All that we know positively on the subject is, that, in the ordinary exercise of vision, the mind, from the position of any impression on the retina, infers the position of the object in relation to the eye, and the rest of the body.

The question still remains, whether the inference, in such a case, is the effect of intuition or of experience; the operation entirely of a law of our constitution, or the result of habit.

In the lower animals, and especially in those of them whose sense of touch is coarsely developed, the inferences drawn from sight must be altogether intuitive. Sir James Hall, having been engaged in making experiments on the hatching of eggs by means of artificial heat, on one occasion observed in one of his boxes a chicken in the act of breaking from its confinement. Just as the creature got out of the shell, it darted forward, seized, and swallowed a spider, which caught its eye, running along the box.[23]

I have observed a child, a few minutes after it was born, follow a candle with a lateral motion of both eyes, as perfectly as if it had been a year old. A child's knowledge of the multifarious properties of material objects, however, is gradually acquired, and a considerable share of it is to be ascribed to experience, or to the associated perceptions of touch and sight. Berkeley maintained, that the ideas of sight are altogether unlike those of touch, and that since the notions we have of an object by these different senses have no similitude, we can learn only by experience how one sense will be affected, by what, in a certain manner, affects the other. Finding from experience, that an object in an erect position, affects the eye in one manner, and the same object in an inverted position, affects it in another, we learn to judge, by the manner in which the eye is affected, whether the object is erect or inverted. Visible ideas, according to Berkeley, are signs of the tangible; and the mind passes from the sign to the thing signified, not by means of any similitude between the one and the other, nor by any natural principle; but by having found them constantly conjoined in experience, as the sounds of a language are with the things they signify.[24]

An attempt has been made by Dr Alison[25] to explain erect vision, with inverted images, on the ground that the origin of the optic nerves is such, that the filaments ending in the upper part of the retina come from the lower part of the corpora quadrigemina, and *vice versâ*.

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[1] Zur vergleichenden Physiologie des Gesichtssinnes, Taf. ii. fig. 1; Leipzig 1826.

[2] Beiträge zur Aufklärung der Erscheinungen und Gesetze des Organischen Lebens, Heft ii. 42; Heft iii. 91; Bremen 1836, 1837.
[3] Müller's Archiv für Anatomie, Physiologie und wissenschaftliche Medicin; Jahrgang 1837, p. viii.
[4] Treatise on the Eye, i. 384; Edinburgh 1759.
[5] Medical Essays and Observations, by a Society in Edinburgh, iv. 202; Edinburgh 1752.
[6] Lectures on Natural Philosophy, ii. 575; London 1807.
[7] Beobachtungen und Versuche zur Physiologie der Sinne, i. 89; Prag 1823.
[8] Ib. ii. 117; Berlin 1825.
[9] Commentationes Societatis Regiæ Gottingensis, xiii; Gottingæ 1799.
[10] Oeuvres, 527, fig. 1; Leide 1717.
[11] Ib. 496. Philosophical Transactions, May 18, 1668.
[12] Commentarii Academiæ Scientiarum Imperialis Petropolitanæ, i. 316; Petropoli 1728.
[13] Op. Cit. ii. 227; Edinburgh 1759.
[14] Ib. 225.
[15] Op. Cit. ii. 583; London 1807.
[16] Op. Cit. 315.
[17] London Medical Gazette, xxii. 230; London 1838.
[18] Ad Vitellionem Paralipomena, quibus Astronomiæ pars optica traditur, 173; Francofurti 1604.
[19] Treatise of Optics, 115; London 1775.
[20] Op. Cit. 226.
[21] Treatise on Optics, 294; London 1831.
[22] Op. cit. 224.
[23] Illustrations of Phrenology, by Sir G. S. Mackenzie, 38; Edinburgh 1820.
[24] Reid's Inquiry into the Human Mind. Chap. vi. Sect. 11.
[25] Transactions of the Royal Society of Edinburgh, xiii. 484; Edinburgh 1836.

CHAPTER XVI.

MONOCULAR AND BINOCULAR VISION. SINGLE VISION WITH TWO EYES.

§ 125. *Single vision. Double vision.*

When we direct our eyes to any object, we receive two impressions from it, one on each retina; each of these impres-

sions by itself would enable us to see the object; yet, by both together, we, in ordinary circumstances, still see it only single.

When the object to which we direct our eyes is at a great distance, the optic axes are nearly parallel to each other, and the image falls on the vertex of each retina; when the object is brought nearer to us, we converge the optic axes towards it by means of the muscles of the eye, so that the images may fall as near to the vertices of the retinæ as possible. In both cases, the object appears single.

An object, nearer to the eyes, or more distant from them, than that to which the optic axes are directed, appears double. Thus, if a candle is placed at C, fig. 92, straight before the eyes, A, B, and ten feet distant from them, the axes of both eyes, A C, B C, being directed to the candle, it appears single. But if the student hold his finger at arm's length between his eyes and the candle, say at *f*, when he looks at the candle, he will see his finger double, and when he looks at his finger, he will see the candle double.

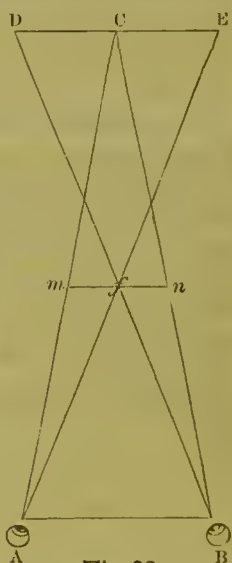

Fig. 92.

Place the object *f* any where within the angle A C B, and direct the optic axes to C, and *f* will appear in two places; for being seen by the right eye in the direction of the visual line B *f*, it must appear on the left side of C, and its distance from C will be measured by the angle C B *f*; and, being seen by the left eye in the direction of the visual line A *f*, it must appear on the right side of C, and its distance from C will be measured by the angle C A *f*. Consequently, it must appear double, and the distance between the places of its appearance will be measured by the sum of the angles C B *f*, C A *f*.

As soon as the eyes change their direction from C to *f*, the object *f* appears single; but all objects within the angle D *f* E, formed by the optic axes produced, appear double. Thus,

the object C, being seen in the visual lines A C, B C, which are on different sides of the object *f*, must necessarily appear double, and the distance between the places of its appearance is measured by the sum of the angles C A E, C B D.

By pressure with the finger on one of the eyes, we may so displace it, that, while in the other eye, the image of an object falls on the vertex of the retina, in the displaced eye the image falls to one side of the vertex. Double vision is the consequence. It is generally stated, that in the transverse plane, the eye must be considerably inclined to produce this effect; but that in the vertical plane, a very slight inclination is sufficient to cause it. Hence it is inferred, that the limits of the field of single vision form an ellipse, of which the long axis corresponds to the transverse axis of the eyeball, and the short to the vertical axis.

§ 126. *Explanation of terms. Corresponding or identical points of the retinæ. Horopter. Plane of the horopter.*

Before proceeding farther, it is necessary to explain certain terms, which frequently occur in the consideration of the much agitated question of single vision with two eyes.

1. *Corresponding or identical points of the retinæ.* It has generally been supposed, that single vision results, only when certain corresponding or identical parts of the two retinæ are affected simultaneously; and that if other parts of the retinæ receive the images of the object, it is seen double.

Professor Müller is of opinion that a knowledge of the identical parts of the retinæ may be obtained by observing the effects of pressure on the eyeball. Thus, if we exert pressure with the finger at the upper part of one eye, and at the lower part of the other, two luminous spectra are produced, one above the other; the upper spectrum resulting from the pressure made at the lower part of the one eye, and the lower from that made at the upper part of the other eye. These points in the retinæ of the two eyes are therefore certainly not identical; for affections of them are referred to perfectly different parts of the field of vision.

If pressure be made on the outer part of both eyes, two spectra are seen, of which the one belonging to each eye is on the opposite side in the field of vision. If the inner side of each eye be pressed, two spectra are produced, but they lie at the extreme limits of the field of vision; the one on the right side belonging to the right eye, and that on the left to the left eye. It is certain, therefore, that neither the outer lateral parts of the two retinæ, nor their inner lateral parts are identical.

The outer portion of the one retina is supposed to be identical with the inner portion of the other; the upper part of the one to be identical with the upper part of the other; and the lower parts of the two to be identical. Pressure being made on both eyes simultaneously at their lower part, while they are closed and no light is shining upon them, one luminous ring is seen at the middle of the upper part of the field of vision; if the upper part of both is pressed, a single luminous circle appears below. If the right side of both eyes is pressed, a single spectrum is seen at the extreme left of the field of vision; and *vice versâ*.

Professor Müller concludes that parts of the two retinæ which lie at equal distances from the vertex, and in the same direction, that is, both to the right, or both to the left, both upward or both downward, are identical; and all other parts non-identical.

2. *Horopter. Plane of the horopter.* According to Aguilonius,[1] all objects seen at the same glance with both eyes appear to be in the plane of the horopter. The horopter, from ὅρος *boundary* and ὁπτομαι *I see*, he defines to be a line drawn through the point of intersection of the optic axes, and parallel to the line joining the centres of the two pupils; the plane of the horopter to be a plane passing through this line at right angles to that of the optic axes.

When the eyes are directed to C, fig. 92, a double image of *f* is seen at D and E, in the horopter D C E; and when the eyes are directed to *f*, a double image of C is seen at *m* and *n*, in the horopter *m f n*.

§ 127. *Phenomena of Binocular vision.*

We owe to Mr Wheatstone a knowledge of some optical facts so interesting in themselves, and bearing so strongly on the question of single vision with two eyes, that I consider it necessary, before going farther, to present the reader with the following abstract of his observations.[2]

When an object is viewed at so great a distance that the optic axes are sensibly parallel, the perspective projections of it, seen by each eye separately, are similar, and the appearance to the two eyes is precisely the same as when the object is seen by one eye only. There is, in such a case, no difference between the visual appearance of an object in relief and its perspective projection on a plane surface. Hence, pictorial representations of distant objects, when those circumstances which would prevent or disturb the illusion are carefully excluded, may be rendered such perfect resemblances as to be mistaken for the objects themselves: of which the diorama affords an instance. This similarity no longer exists when the object is placed so near the eyes that to view it the optic axes must converge. In this case, Mr Wheatstone has shown, that a different perspective projection of the object is seen by each eye, and that these perspectives are more dissimilar in proportion as the convergence of the optic axes becomes greater. The student may easily verify this fact, by holding a pencil horizontally before his eyes, the one end pointing towards him and the other from him, and while the head is kept perfectly steady, viewing it with each eye successively, while the other

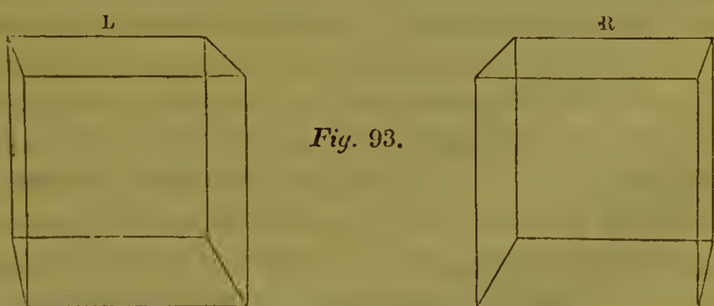

Fig. 93.

is closed. Figure 93 represents the two perspective projec-

tions of a cube, placed about seven inches immediately before the observer, and viewed in this manner; R being the projection seen by the right eye, and L that presented to the left.

The appearances, rendered obvious by these simple experiments, may easily be inferred from the established laws of perspective; for the same object in relief, when viewed first by one eye and then by the other, is seen from two points of sight separated by a distance equal to the line joining the two eyes. Mr Wheatstone ascribes the inattention of philosophers to this fact, to the circumstance, that the results are contrary to the principle generally maintained by optical writers, that objects can be seen single only when their images fall on corresponding points of the retinæ. If the consideration, then, ever arose in their minds, it was hastily discarded, under the conviction, that, if the images presented to the two eyes are under certain circumstances dissimilar, the differences must be too small to be taken into account.

Mr Wheatstone's discovery explains why it is impossible for an artist to give a faithful representation of any near solid object; that is, to produce a painting which shall not be distinguished in the mind from the object itself. When the painting and the object are seen with both eyes, in the case of the painting two *similar* pictures are projected on the retinæ, but in the case of the solid object the pictures are *dissimilar*. There is therefore an essential difference between the impressions on the organs of sensation in the two cases, and consequently between the perceptions formed in the mind. Hence the painting cannot be confounded with the solid object.

Having established that the mind perceives an object of three dimensions by means of dissimilar images projected by it on the two retinæ, Mr Wheatstone goes on to inquire into the visual effect of presenting to the eyes, instead of the object itself, its projection on a plane surface as it appears to each eye separately. To pursue this inquiry, means must be employed to make the two pictures, which necessarily occupy different places, fall on similar parts of the retinæ. Under the ordinary circumstances of vision, the object is seen at the concourse of the optic axes, and its images consequently

are projected on similar parts of the two retinæ; but it is also evident that two exactly similar objects may be made to fall on similar parts of the two retinæ, if they are placed one in the direction of each optic axis, at equal distances before or beyond their intersection.

In fig. 94, let *a* represent the usual situation of an object, at the intersection of the optic axes, E *a*, E′ *a*; *b b*, two similar objects placed in the direction of the optic axes before their intersection; and *c*, *c*, other two similar objects placed beyond it. In all these three cases, the optic axes being converged towards *a*, the mind perceives but a single object, and refers it to the place where the optic axes meet. When the eyes converge beyond the objects, as when these are placed at *b*, *b*, the right hand object is seen by the right eye, and the left hand object by the left eye; but when the axes converge nearer than the objects, *c*, *c*, the right hand object is seen by the left eye, and conversely. As both these modes of vision are forced and unnatural, eyes unaccustomed to such experiments require some artificial assistance; and Mr Wheatstone describes instruments by which the coincidence of the images is facilitated.

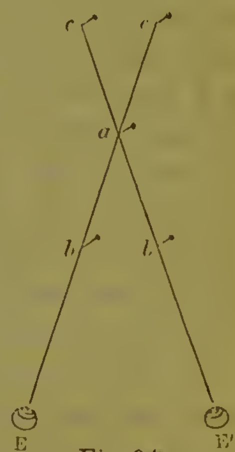

Fig. 94.

If, instead of placing two exactly similar objects before the eyes, two perspective projections of the same solid object be employed, the mind will still perceive a single object, but instead of a representation on a plane surface, as each drawing appears when separately viewed by the eye directed towards it, the observer will perceive a figure of three dimensions, the exact counterpart of the object from which the drawings were made.

By means of an instrument invented by Mr Wheatstone, and called by him a *stereoscope*[3] from its property of representing solid figures, the two pictures, or rather their reflected images, are placed at the true concourse of the optic axes, the eyes preserve their usual focal adjustment, the appearance of lateral images is avoided, and a large field of view for each

eye is obtained. The essential parts of this instrument are two plane mirrors, so placed that their backs incline towards each other at an angle of 90°. The two pictures, such as R, L, fig. 93, are placed by the sides of the mirrors, parallel to each other, and in such a manner that their corresponding horizontal lines are on the same level. The observer, bringing his eyes close to the mirrors, the right eye before the right hand mirror, and the left eye before the left hand mirror, sees as if the solid body stood forward in relief, provided the two perspective drawings of it are so situated that their images, reflected by the mirrors, coincide at the intersection of the optic axes. As the drawings are reversed by reflection in the mirrors, the perspective of the object as seen by the right eye must be presented to the left hand mirror, and *vice versâ*.

Mr Wheatstone's experiments render it evident, that there is an essential difference in the appearance of objects when seen with two eyes, and when only one eye is employed, and that the vivid belief which we have of the solidity of an object of three dimensions arises only when two different perspective projections of it are simultaneously presented to us. How happens it then, it may be asked, that persons who see with only one eye form correct notions of solid objects, and never mistake them for pictures? How happens it also, that a person having the perfect use of both eyes, perceives no difference in objects around him when he shuts one of them? In explanation of these apparent difficulties, Mr Wheatstone observes, that although the simultaneous vision of two dissimilar pictures suggests the relief of objects in the most vivid manner, yet there are other signs which suggest the same idea to the mind, which, though more ambiguous than the former, become less liable to mislead the judgment in proportion to the extent of our previous experience. The vividness of relief arising from the projection of dissimilar pictures, one on each retina, becomes less and less as the object is seen from a greater distance, and entirely ceases when the object is so distant that the optic axes are parallel. All objects beyond this distance are seen with both eyes precisely as we see near objects with a single eye; for the pictures on the two retinæ are then

exactly similar, and whether identical pictures fall on corresponding parts of the two retinæ, or one eye only is impressed with one of these pictures, passes without being apprehended by the mind. A person deprived of the sight of one eye sees, therefore, all external objects, near and remote, as a person with both eyes sees remote objects only. The vivid effect arising from binocular vision of near objects is not perceived by a person with one eye; and to supply this deficiency he has recourse unconsciously to other means of acquiring more accurate information. The motion of the head is the principal means he employs. That the required knowledge may be thus obtained will be evident from the following considerations. The mind associates with the idea of a solid object every different projection of it which experience has hitherto afforded; a single projection may be ambiguous, from its being also one of the projections of a picture, or of some other solid object; but when different projections of the same object are successively presented, they cannot all belong to another object, and the form to which they actually belong is completely characterized. While the object remains fixed, at every movement of the head it is viewed from a different point of sight, and the picture on the retina consequently continually changes.

The observations of Mr Wheatstone, already quoted, afford ample proof that objects, the images of which do not fall on corresponding points of the two retinæ, may still appear single. He is also of opinion that similar images falling on corresponding points of the two retinæ may appear double and in different places; but for the proofs adduced in favour of this point, I must refer to the original paper. Mr Wheatstone concludes from them, that there is no necessary physiological connexion between the corresponding points of the two retinæ.

His next inquiry is into the effect of presenting similar images, but differing in magnitude, to analogous parts of the two retinæ. For this purpose two squares or circles, differing obviously but not extravagantly in size, may be drawn on two separate pieces of paper, and placed in the

stereoscope so that the reflected image of each shall be equally distant from the eye by which it is regarded. Notwithstanding their difference, they coalesce and occasion a single perception. The limit of the difference of size within which the single appearance subsists may be ascertained by employing two images of equal magnitude, and causing one of them to recede from the eye while the other remains at a constant distance.

Though the single appearance of two images, differing in size, is by this experiment demonstrated, the observer is unable to perceive what difference exists between the apparent magnitude of the binocular image and that of the two monocular images. To determine this point, the stereoscope must be dispensed with, and the experiment so arranged that all three shall be simultaneously seen. This may be done by placing the two drawings side by side on a plane before the eyes, and converging the optic axes to a nearer point, or to a more distant one, as in fig. 94, until the three images are seen at the same time, the binocular image in the middle, and the monocular images at each side. The binocular image then appears intermediate in size between the two monocular ones.

If the pictures be too unequal, the binocular coincidence does not take place. It appears, that if the inequality of the pictures be greater than the difference which exists between the two projections of the same object when seen with both eyes turned to the extreme right or to the extreme left, they do not coalesce. Were it not for the binocular coincidence of two images of different magnitude, objects would appear single only when the optic axes converge directly forward; for it is only when the converging visual lines form equal angles with the visual base, or line joining the centres of the two pupils, that the two images can be of equal magnitude. When they form different angles with it, the distance from the object to each eye is different, and consequently the picture projected on each retina has a different magnitude. If we hold a shilling to our extreme right, while the optic axes converge to a nearer point than the piece of money, it will appear

double, and the image of it seen by the left eye will be evidently smaller than that seen by the right.

If we regard a picture with the right eye alone for a considerable time, it will continue to be perceived for a short period after removal from the field of view; if we look at another and dissimilar picture with the left eye alone, its effect will be equally permanent. It might therefore be expected, that if each picture were presented to its corresponding eye at the same time, the two would appear permanently superposed on each other. Mr Wheatstone found, that, contrary to expectation, this was not the case.

If two letters, such as S and A, half an inch long, and each enclosed within a circle, be presented at the same time, the one to the right and the other to the left eye, the common border will remain constant, while the letter within will change alternately from that which would be perceived by the right eye alone to that which would be perceived by the left alone. At the moment of change, the letter which has just been seen breaks into fragments, while fragments of the letter which is about to appear mingle with them, and are immediately after replaced by the entire letter. It does not appear to be in the power of the will to determine the appearance of either of the letters, but the duration of the appearance depends on causes under control. Thus, if the two pictures be equally illuminated, the alternations are generally of equal duration; but if one be more illuminated than the other, that which is less so will be perceived during a shorter time.

These observations of Mr Wheatstone are confirmatory of the experiments of Du Tour,[4] in which two different colours were allowed to fall on corresponding parts of the two retinæ. If a blue disc be presented to the right eye, and a yellow disc to the corresponding part of the left, instead of a green disc, which would appear if the colours had mingled before their arrival at a single eye, the mind will perceive the blue and the yellow predominating in turns, either partially or wholly over the disc. In the same manner, the mind perceives no trace of violet when red is presented to one eye and blue to the other, nor any vestige of orange when red and yellow are separately

presented in a similar manner. These experiments may be conveniently repeated by placing the coloured discs in the stereoscope, but they are usually made by looking at a white object through differently coloured glasses, one applied to each eye.

§ 128. *Theories of single vision with two eyes.*

The law of visible direction for binocular vision, ought, as Mr Wheatstone observes, to contain nothing inconsistent with the law of visible direction for monocular vision.

1. According to Aguilonius, all objects which are in the plane of the horopter (§ 126) must appear single, because the lines of direction in which any point of an object is seen coincide in this plane and nowhere else; and as these lines can meet each other only in one point, it follows from the hypothesis, that all objects not in the plane of the horopter must appear double, because their lines of direction intersect each other, either before or after they pass through it. That this opinion, which was adopted by Porterfield, is erroneous, is sufficiently shown by the fact mentioned by Wheatstone, that, when the optic axes converge to any point, objects before or beyond the plane of the horopter are under certain circumstances seen single equally as those in that plane.

2. Dr Wells[5] held with Aguilonius, that objects are seen single, only when situated in the plane of the horopter, and consequently that they appear double when they are either before or beyond it; but he attempted to make this single appearance of objects only in the plane of the horopter to depend on other principles, from which he deduced, contrary to Aguilonius, that the objects which are doubled do not appear in the plane of the horopter, but in other places which are determined by these principles. Dr Wells was led to his new theory by an instance of binocular vision of relief which he accidentally observed, and which he could not reconcile with any existing theory of visible direction.[6] Framed to account for an anomalous individual fact, Dr Wells's theory is inconsistent with the general rules on which that fact has been shown by Mr Wheatstone to depend.

3. That an object is seen single because its images fall on corresponding or identical points (§ 126) of the two retinæ, is the theory which has met with the greatest number of supporters. It supposes that corresponding points of the images falling on corresponding points of the retinæ, the two impressions are exactly similar to each other.

Authors who agree in adopting this hypothesis, differ widely in explaining why objects are seen in the same place, or single, when their images fall on corresponding points of the retinæ. Smith makes it depend on the predominance of the sense of touch, constantly informing us that the object is single. Reid concludes that it is probably the consequence of a primary law of our constitution. Galen, Briggs, Newton, Rohault, Wollaston, Müller, and Alison, have regarded it as depending on the anatomical structure of the chiasma, and the connexion of the two optic nerves.

Mr Wheatstone has pointed out the inconsistency of the theory of corresponding points with the law of Aguilonius; for corresponding lines of visible direction, that is, lines terminating in corresponding points of the two retinæ, cannot meet in the plane of the horopter unless the optic axes be parallel, and the plane at an infinite distance.

The law of corresponding points, carried to its necessary consequences, leads to the conclusion, that no object can appear single unless it is seen in a circle, the circumference of which passes through the centres of visible direction of each eye and the point of convergence of the optic axes. Hence Professor Müller, on the hypothesis of corresponding points, contends that the true form of the horopter is a circle.

The same reasons which disprove the theory of Aguilonius, lead Mr Wheatstone to reject the law of corresponding points, as an inaccurate expression of the phenomena of single vision. According to the former hypothesis, objects can appear single only in the plane of the horopter; according to the latter, only when they are in the circle of single vision. Both positions are inconsistent with the binocular vision of objects in relief, for the points of which the objects consist appear single though they are at different distances before the eyes. The supposi-

tion, admitted by all the followers of the theory of corresponding points, that the images projected by any object on the two retinæ are exactly similar, is incontrovertibly proved by Mr Wheatstone's experiments to be contrary to fact, in every case except that in which the optic axes are parallel.

4. In many persons, the eyes are unequal in focal length, so that when they read, or look at any near object, they use chiefly the one eye, and when they regard distant objects, they employ chiefly the other. When such a person, with both eyes open, covers a distant object by the interposition of his finger, he finds on shutting his short-sighted eye that the finger continues to cover the distant object, but if the long-sighted eye be closed and the short-sighted opened, the relative situation of the finger and the distant object will appear altered, the distant object now appearing uncovered; proving, that in directing the finger to cover the distant object, the long-sighted eye had alone been employed. Such experiments, ill understood, have given rise to the notion of Gassendi, Haller, Gall, and others, that we see with only one eye at a time, though both remain open; the one being relaxed and inattentive to objects, while the other is on the stretch. A sufficient refutation of this hypothesis is afforded by the fact that the simultaneous affection of the two retinæ excites a different idea in the mind, from that which is consequent to either of the single impressions; the latter giving rise to the idea of a representation on a plane surface, the former to that of an object in relief.

Du Tour held that though we may occasionally see at the same time with both eyes, yet the mind cannot be affected simultaneously by corresponding points of the two images. He was led to this opinion, from the results of his experiments (§ 127) with glasses of different colours. Mr Wheatstone remarks, that it would be difficult to disprove Du Tour's conjectures by experiment; but that all that the facts adduced in its favour, as well as other facts relating to the disappearance of objects to one eye, really prove, is, that the mind becomes inattentive to impressions made on one retina, when it cannot combine the impressions on the two retinæ together.

§ 129. *Cause of vision in relief by dissimilar images on the retinæ.*

Mr Wheatstone concludes his ingenious paper, by examining why dissimilar images projected on the two retinæ give rise to the perception of an object in relief. He does not attempt the complete solution of this difficult and complex question, but merely considers the most obvious explanation which might be offered, and shows its insufficiency to explain the whole of the phenomena.

It might be supposed, that we see distinctly, at the same instant, only that point of a field of view to which the optic axes are directed, while all other parts are seen so indistinctly, that the mind does not recognise them to be either single or double, and that the figure is appreciated by directing the converging optic axes successively to a sufficient number of its points to enable us to judge accurately of its form.

Were this entirely true, no appearance of relief should present itself when the eyes remain intently fixed on one point of a binocular image in the stereoscope, which Mr Wheatstone finds, however, to be the case. He adduces various proofs that the appearance of relief is an effect independent of any motion of the eye.

When an object, or a part of an object, appears in relief while the optic axes are directed to a single binocular point, each point which appears single is seen at the intersection of the lines of visible direction in which it would be seen by each eye separately, whether these lines terminate at corresponding points of the two retinæ or not.

But the converse of this, *viz.* that every point of an object in relief is seen by a single glance at the intersection of the lines of visible direction in which it would be seen by each eye singly, does not hold; for on this supposition an object before or beyond the intersection of the optic axes should never appear double. The determination of the points which shall appear single seems to depend in no small degree on our previous knowledge of the form we are regarding.

Mr Wheatstone thinks it probable, that some law of vision may be discovered, which shall include all the circumstances under which single vision by means of non-corresponding points occurs and is limited. On the whole, he concludes, that sufficient has been shown, to prove that the laws of binocular visible direction, hitherto laid down, are too restricted to be true. The law of Aguilonius assumes that objects in the plane of the horopter are alone seen single; and the law of corresponding points that no object appears single unless it is seen in a circle whose circumference embraces the centres of visible direction and the point of convergence of the optic axes. Both are inconsistent with the fact, that objects do appear single whose points lie out of the plane and out of the circle. Should it be hereafter proved, that all points in the plane or in the circle are seen single, (and from the great indistinctness of lateral images, it will be difficult to give this proof,) the law must be qualified by the admission, that points out of them do not always appear double.

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[1] Opticorum Libri vi. 110; Antverpiæ 1613.

[2] Philosophical Transactions for 1838, 371.

[3] *Stereoscope,* from στερεὸς *solid,* and σκοπέω *I look at.*

[4] Mémoires de Mathématique et de Physique, présentés à l' Académie Royale des Sciences, iii. 514, iv. 499; Paris 1760, 1763.

[5] Essay upon Single Vision with Two Eyes, 5; London 1818.

[6] Ib. 38.

CHAPTER XVII.

COLOURS OF EXTERNAL BODIES. COMPLEMENTARY COLOURS.

§ 130. *Production of colours by unequal absorption and reflection of the coloured rays of light. Brewster's analysis of the solar spectrum by absorption.*

ALL that we perceive originally by the sense of vision is the colours of external bodies (§ 1).

The production of colours by the decomposition of white light, as it passes through refracting media, has already demanded our attention (§ 67, 68, 69).

It is evident, that the colours commonly presented to us by external bodies are not produced by refraction. Neither are they qualities inherent in the bodies themselves, but consequences merely of a peculiar disposition of the particles of each body, by which it is enabled to reflect the rays of one particular colour, and to transmit, or to absorb, the others. Bodies that reflect all the rays appear white, those that absorb them all are black; but most substances, after effecting a peculiar decomposition of the white light which falls upon them, reflect some colours, and transmit or absorb the rest.

The simple fact, that every body, whatever be its colour in white light, when exposed in the prismatic spectrum, appears of the colour of that part of the spectrum in which it is placed, affords a direct and satisfactory proof of the doctrine, that the ordinary colour of bodies depends on their unequal absorption and reflection of the coloured rays of light.

Upon the same property depend the colours of transparent media; for they also derive their colours from their power of absorbing some of the rays and transmitting others.

Taking advantage of the power of absorbing different

colours possessed by different media, Sir David Brewster has accomplished a new analysis of the solar spectrum.

If the prismatic spectrum, V R, fig. 65, be viewed through a piece of blue smalt glass, like what is sometimes used for finger glasses, it appears deficient in a certain number of its colours. The blue glass, if of a certain thickness, absorbs the middle of the red space, the whole of the orange, a great part of the green, a considerable part of the blue, a little of the indigo, and still less of the violet. The yellow space, which is scarcely acted on, is increased in breadth, and now occupies part of the space formerly covered by the orange on the one side, and part of the space formerly covered by the green on the other. Hence it follows, that the blue glass has absorbed the red light, which, when mixed with the yellow, constituted orange, and has absorbed also the blue light, which, when mixed with the yellow, constituted the part of the green space next to the yellow. The orange and green rays of the spectrum, though they cannot be decomposed by prismatic refraction, are decomposed by absorption, and actually consist each of two different colours possessing the same degree of refrangibility.

Sir David Brewster, on examining the spectra produced by various bodies, and the changes which they undergo by absorption when viewed through different coloured media, found that the colour of every part of the spectrum may be thereby changed, not only in intensity, but in colour; and from these observations, he came to the conclusion, that the prismatic spectrum consists, not of seven, but of three primary colours, red, yellow, and blue. Each of these three exists throughout the whole length of the prismatic spectrum, but with different degrees of intensity in different parts of its extent, the seven colours being produced according to the excess or defect of the three several primary colours.

§ 131. *Production of colours by the interference of light. Corpuscular and undulatory theories of light.*

Besides the unequal absorption of the prismatic rays, which

is the cause on which the ordinary colours of material substances depend, there is another cause which operates in certain circumstances, and, amongst other phenomena, gives rise to the iridescent appearance observed in soap bubbles, on the surface of mother-of-pearl, in the feathers of the peacock's tail, &c. The cause in question is termed the *interference of light.*

We have already had occasion (Note 3, page 206) to mention, that the shadows of bodies, placed in the diffused cone, formed by a pencil of light admitted through a small hole into a darkened chamber, are magnified by inflection, and fringed with colours. This is one example of the production of colours by interference.

If a pencil of homogeneous light, such as the red light of the prismatic spectrum, be admitted into a dark room through a pin-hole, about $\frac{1}{40}$ inch in diameter, and a slender wire be held in the light, the shadow of the wire, received on a sheet of paper, is seen to consist of a series of alternate red and black stripes on each side. That the alternation of these stripes arises from the interference of the two streams of light which flow round the wire, is proved by their vanishing, the instant that one of the streams is interrupted. It is therefore concluded, that, as often as the stripes of light and darkness occur, they are owing to the rays combining at certain intervals to produce a joint effect, and at others to destroy one another.

Philosophers have formed two hypotheses, the *corpuscular* and the *undulatory*, to explain the manner in which vision is produced by luminous objects.

The corpuscular hypothesis, which was the one adopted by Newton, is, that light consists of very small particles of matter, which are continually thrown off from luminous bodies, and which produce the sensations of vision by actual impact on the retina.

Huygens and Young, on the other hand, suppose that all space is occupied, and every material body pervaded, by an extremely rare, imponderable, and highly elastic medium, or ether, capable of being thrown into undulations by the action

of luminous bodies, which undulations constitute light, and being transmitted to the retina, produce the impressions necessary for vision.

The undulatory theory requires us to admit a very considerable number of postulates, and among the rest, that as in the doctrine of sound the frequency of the aerial pulses, or the number of excursions to and fro made by each molecule of the air, determines the *pitch* or *note*, so in the theory of light the frequency of the pulses or number of impulses on the retina in a given time by the ethereal molecules determines the *colour* of the light; and that as the absolute extent of the motion to and fro of the particles of the air determines the *loudness* of the sound, so the amplitude or extent of the excursions of the ethereal molecules determines the *brightness* or *intensity* of the light.

On account of its elastic nature, one molecule of the luminiferous ether, when set in motion by the action of a luminous body, is supposed to communicate its vibrations to those adjacent. The motions of the ethereal molecules are presumed to be always at right angles to the direction of the rays of light; and are quite different from the undulatory movement which proceeds through the ether, like a wave in water.

By the corpuscular theory, it is not easy to account for such phenomena as are presented to our observation in the experiment above mentioned, for it is contrary to all our ideas of matter to suppose that under any circumstances two particles of it should annihilate one another; but on the undulatory hypothesis, a plausible explanation is afforded. Two opposing motions may destroy each other, and it is impossible not to be struck with the analogy between the effects produced by the interferences of air, or of water, and the luminous phenomena in question. Two equal waves of water, proceeding from centres near each other, are seen to destroy each other's effects at certain points, and at other points to redouble them; and what is technically called the *beating* of two sounds is explained from a similar interference. The same principles have been applied by Dr Young to the alternate union and extinction of colours.

The following is the explanation of the experiment above noticed, afforded by the undulatory hypothesis and the doctrine of interference.

The rays, bending round the wire in two streams, and meeting in the middle of the shadow, are of equal lengths, and the stripe which they form is red. All the other rays, which bend round the wire to meet in the shadow, are unequal in length, and by interfering with each other either add to the intensity of the light, or destroy it; giving rise in the one case to red stripes, and in the other to black. If of two rays bending round the wire and interfering with each other, the one has passed through an entire undulation more than the other, the two will increase each other's intensity; and the same effect will result, if the difference in their length amounts to two or any greater number of entire undulations. But if, on the contrary, a ray from the one side of the wire meets another from the opposite side, and the one has passed through only half an undulation more than the other, the convex or elevated part of the undulation of the one ray will interfere with the concave or depressed part of the undulation of the other, so that both will be destroyed, and the spot on which they fall will be destitute of colour.

If white light be used in the experiment, instead of alternate stripes of red and black, stripes of the different prismatic colours are seen. The waves of each colour, contained in white light, being of different lengths, each of the prismatic colours produces in the shadow received on the sheet of paper, its own separate coloured and black stripes in the same way as when a single colour is employed.

In order that two portions of light may interfere, it is necessary that they be derived from the same origin, and that they arrive at the same point by different paths, in directions not much deviating from each other. The deviation may be produced, in one or both portions, by inflection, by reflection, by refraction, or by any of these effects combined.

The doctrine of interference explains very readily the colours produced by thin transparent laminæ, finely grooved surfaces, and minute fibres. Falling, for example, upon a

soap bubble, light is partially reflected from both the surfaces of the thin plate of which it is formed; the portions into which the light is divided are brought again together by the double reflection which they undergo; and, the difference in the length of the paths which the rays have traversed is such that the appearances due to interference are produced.

§ 132. *Complementary colours. Ocular spectra.*

If the retina is fatigued by the impression of any particular colour, it loses for a time its sensibility to that colour, but continues to be affected, or as if it were affected, by the other constituent parts of white light.

If, for example, we look steadily for a few minutes at a sheet of green paper, and then turn our eyes to a sheet of white paper, the paper does not appear white, but red. The physical explanation offered of this fact is, that the retina has become insensible to the green rays, forming part of the white light reflected from the paper; the consequence of which is, that, if the colour with which the retina was fatigued was the prismatic green, the white paper now seems of a colour arising from a union of all the rays in white light but the green. That this explanation is not perfectly true is evident from the observation of Professor Müller, that the red appearance is produced although the eye is directed upon a black surface, or completely excluded from light.

In like manner, if after fixing the eye steadily for some minutes on a red wafer, placed on a sheet of white paper, we turn the eye to another part of the paper, a green spectrum appears of the same size as the wafer.

The spectrum, thus produced, continues for some time, is perceived even with the eyes closed, follows the motions of the eyes, and gradually fades away. The colours of such spectra were originally called by Boyle *adventitious*, Buffon termed them *accidental*, but latterly they have received the name of *complementary colours;* because, when produced by any of the prismatic colours, the colour of the spectrum is exactly that which if added to the colour by which the retina

has been fatigued would complete the prismatic spectrum, or, by being combined with that colour, would form white light.

The following table shows the complementary colours of the seven prismatic colours :—

Prismatic colour.	Complementary colour.
Red, . .	Bluish green.
Orange, . .	Blue.
Yellow, . .	Indigo.
Green, . . .	Violet reddish.
Blue, . .	Orange red.
Indigo, . . .	Orange yellow.
Violet, . .	Yellow green.

If we take half the length of the prismatic spectrum in the compasses, and set one foot in the colour, the complementary colour of which is required, the other foot will fall upon the complementary colour; or, if we arrange all the colours of any prismatic spectrum in a circle, in their due proportions, each colour will have its complementary colour diametrically opposite to it.

If we look steadily for some minutes at a white square, enclosed within a black border, on closing the eyes a spectrum appears of a black square enclosed within a white border. Black is therefore the accidental colour of white, and white of black.

If the impression on the retina be by a very strong white light, such as the direct light of the sun, the spectrum is not black, but a succession of various colours.

CHAPTER XVIII.

VISUAL PERCEPTIONS.

§ 133. *Visual perception of figure.*

Our primary perceptions, by the sense of vision, extend only to the presencc of light, the degrees of light and shade, and the colours of bodies. These perceptions enable us to acquire ideas of visible figure and visible place; whence we are led, step by step, to other acquisitions, till at last we learn to recognise by the eye alone almost every thing a knowledge of which we owe to the combined exercise of touch and sight.

The visible appearances of objects serve only as signs of their form, place, size, distances, motions, and other tangible qualities. The visible appearance of any object is that which is presented to the eye, according to those laws of light and vision which we have been considering; but the thing signified to the mind by the visible appearance includes a variety of properties, of which our knowledge is the result of experience in the use of sight, corrected by touch. So thoroughly combined at last in our minds are the perceptions acquired by touch with those which we owe to sight, that it is almost impossible for us to disentangle in our thoughts the propcr objects of the one sense from those of the other.

If a human being, who had prcviously been totally devoid of sight, and had nevcr evcn heard of visual perception, but who had cnjoyed the usc of the sense of touch, wcre suddenly to acquire the power of vision, and if two figures, the onc that of a triangle and the other that of a circle, were the first objects presented to his eyes, and werc placcd side by side, with their superficics perpendicular to his optic axes, he would at once distinguish the one figurc from thc other, and their posi-

tions relatively to one another. Already acquainted with the tangible figures of a triangle and a circle, it seems probable that he would also be able to distinguish the two by their visible figures. But it is plain, that if the two figures, instead of being so placed that their superficies was perpendicular to his optic axes, were presented obliquely to his eyes, it would be impossible for him to judge accurately of the form of the two objects from their visible figures. Neither could he form any idea of their size or distance, in whatever position they might be placed. We estimate the size of objects very much by our knowledge of their distances, but to such an individual as we have been supposing, all objects, at whatever distance, would seem equally near; they would seem to be in his eyes, or in his mind, without ever exciting the idea of distance at all.

Although the eye is sufficient to enable us to distinguish figures of two dimensions, provided they be placed with their superficies perpendicular to our optic axes, it could never communicate the idea of a body having length, breadth, and thickness. Our knowledge of solidity is originally derived from the sense of touch. After experience has taught us that certain visual appearances are connected with solidity, we readily pass from the sign to the thing signified. Our belief in the solidity of a body of three dimensions depends much, as Mr Wheatstone has shown, on a different projection of it being presented at the same time to each eye.

§ 134. *Visual perception of place.*

As the outline of the parts of the retina affected by the rays of light serves for distinguishing superficial forms from each other, so the situation of the parts affected enables us to perceive the place of the object. If the image be in the axis of the eye, we conclude that the object is straight before us; if it be on the left of the retina, that the object is to our right; if it be on the upper part of the retina, that the object is below; and so on of all other situations.

We can never judge, however, how far objects are distant

from each other, or from the axis of vision, unless we know their distance from the eye.

§ 135. *Visual perception of magnitude.*

In point of magnitude, objects must appear differently according to the figure of the cornea and crystalline; so much so, that we can never be sure that an object is seen of equal size by any two individuals.

There are two means by which we judge of the size of objects. The one is their *apparent magnitude*, and the other is the knowledge we have of their *distance*.

It has already (§ 55) been explained, that the apparent magnitude of any object depends on the size of the image on the retina. Objects appearing equally distant, are always seen greater or smaller, according as their images on the retina are greater or smaller; and if their images are equal, the objects will also appear equal. From what was stated in explaining fig. 59, it is evident, that we can never, from the apparent magnitude alone, discover the actual magnitude of the object; for, provided the distances of two objects, such as Q S, $x\,z$, fig. 59, from the focal centre of the eye be proportional to their magnitudes, their images on the retina, and consequently their apparent magnitudes, may be equal, though the one be many times larger than the other. A shilling, held a few inches before the eye, has the same apparent magnitude as the moon.

It is by our knowledge of the distances of objects, then, that we are enabled to correct the errors into which we should be perpetually falling regarding their actual magnitude, were we to judge from their apparent magnitude alone. Hence, when we are in any way misled regarding the distance of an object, we are exceedingly apt to form a false estimate of its size. Astronomy explains to us, that the moon, when on the horizon, is about 4000 miles farther from us, and ought therefore to appear less, whereas she appears much larger, than when at her greatest elevation. This seeming increase of size arises from our mistaking the distance of the moon, and

supposing her to be not very remote from the terrestrial objects behind which she is seen when on the horizon. Viewed through a tube, which prevents us from seeing the interjacent ground, the horizontal moon loses her appearance of unusual magnitude.

§ 136. *Visual perception of distance.*

To some it may seem a paradox, that distance is invisible. Whatever is its extent, it is plain, that as it is a line directed endwise to the eye, it projects one point only on the retina, which point remains invariably the same.

It is universally acknowledged, that the estimate we make of the distance of objects considerably remote, is an act of judgment grounded on experience, rather than one of sense. It is from their apparent magnitude, the force of their colours, and the presence of more or fewer intervening objects, that we infer their distance.

Most optical writers acknowledge, however, that we employ the two following more direct means of judging of the distance of near objects :—

1. When an object is placed so near to us, that the interval between the eyes bears any sensible proportion to its distance, it is supposed that we perceive it to be nearer or farther off according to the size of the angle formed by the optic axes converging towards it.

2. We are supposed to judge of those distances to which the breadth of the pupil bears any sensible magnitude, by the greater or less divergency of the rays, which, emanating from the visible points of objects, reach the eye; those points being judged to be nearest which are seen by the most diverging rays, and the apparent distance increasing as the divergency of the rays decreases, till at length it becomes infinite, when the rays that fall on the pupil are sensibly parallel.

To the doctrine, that these are means which aid in enabling us to judge of distance, Berkeley[1] objects, that as no idea which is not itself perceived can be the means by which we perceive any other idea, it is impossible we can judge of dis-

tance by lines and angles which are not themselves objects of sense, are known only to those skilled in optics, and have in fact no real existence, but are merely introduced by mathematicians into the science of optics, that they may treat it in a geometrical way.

He admits, however, in the *first* place, that when we look at a near object with both eyes, according as it approaches, or recedes from us, we alter the disposition of our eyes, by lessening or widening the interval between the pupils, and that this disposition of the eyes is attended with a *sensation*, which experience teaches us to connect in the mind with the idea of greater or less distance.

In the *second* place, he admits, that an object placed at a certain distance from the eye, to which the breadth of the pupil bears a considerable proportion, being made to approach, a certain *confusion* in its appearance is produced, and that the nearer it is brought, it is seen the more confusedly. There arises in the mind, therefore, an habitual connexion between the several degrees of confusion and of distance.

To these two means, then, Berkeley chiefly ascribes the judgments we form of the distance of near objects. He adds, indeed, a *third*, the *straining* of the eye which takes place when the appearance of a near object seems confused. It is esteemed so much the nearer, he says, in proportion as the straining of the eyes to obtain distinct vision is greater.

Porterfield, also, enumerates the effort or straining of the eye to accommodate itself to near objects, as one of the means by which the mind judges of distance; forgetting, apparently, that the adjustment takes place, only when we discover the object to be too near to be seen distinctly, without changing the configuration of the eye.

As to the three means by which we judge of the distance of objects considerably remote, no doubt can be entertained.

1. Visible *magnitude* is employed as a sign of distance. By experience, we know the visible magnitude of a man, or any other familiar object, at the distance of ten feet, and we perceive the gradual and proportional diminution of the visible figure of the same object, at the distance of forty feet,

eighty feet, and at greater distances, till it vanish altogether. Hence, a certain visible magnitude of a known object becomes the sign of a certain determinate distance.

2. The force with which the *colours* of distant objects act upon our eyes enables us to judge of their distance. If we previously know that two objects are of one colour, and the same intensity, and if we observe the one brighter than the other, we conclude that the object which appears bright is nearer than the one which appears obscure.

Though the intensity of the light, emanating from any radiant point, decreases as the distance increases, and this in proportion to the square of the distance (§ 7), it does not follow that the force with which objects act on the organ of vision should decrease in the same proportion; for, as the intensity of the light decreases, the visible magnitude also diminishes, and, therefore, unless some new cause come into operation, the image upon the retina should be as lively when the object is distant as when it is near. Such a cause exists in the power possessed by the atmosphere of partially reflecting and absorbing the rays of light, by which means the colours of objects grow fainter and fainter in proportion to their distance.

Porterfield enumerates as a separate means, by which the eye judges of distances, the distinctness or indistinctness in the appearance of the parts of objects; but it is plain that this depends entirely on their visible magnitude and the force of their colours.

When the painter imitates, on the same plane surface, the appearances of objects at very different distances, he studies chiefly the combined effect of the two causes we have been considering. He diminishes the comparative magnitude of those objects which he intends to represent as at a distance, omits all representation of their minute parts, traces their outlines indistinctly, and copies the hazy effect of the intermediate atmosphere.

3. We employ *intervening objects*, whose distance or magnitude is known, as a measure for determining the distance of other objects. Thus, when we look along a street, we form

an estimate of the size and distance of the houses which we see ranged along its sides, and thereby judge of the distance of a man on horseback who is seen crossing it at its farthest extremity. To the inexperienced sailor, land descried at a distance seems much nearer than it really is, from the absence of such intervening objects as could direct his judgment. The horizontal line, in which innumerable objects are interposed between the eye and the horizon, appears much longer than the line of altitude of the meridian.

§ 137. *Visual perception of motion.*

As motion is merely a change of place and distance, it is evident that the means by which we are directed in our judgments of place and distance must direct us also in judging of motion.

1. When a body moves straight to or from our eyes, we judge of its motion by the same means whereby we become sensible of the continued and successive change in its distance.

2. When a body moves in a plane perpendicular to the axis of vision, we judge of its motion from the passage of its image successively over different parts of the retina, if the eye is at rest; but if we follow the body, which is always necessary to obtain distinct vision of it, we judge partly from the motion of the eyes and head, which we employ for keeping the moving body in view, and partly from the notice we take of the objects nearer to us or farther from us, which the moving body crosses in its path.

3. If it moves obliquely, so as to change both its place and its distance, we combine these several means of information.

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[1] Essay towards a new Theory of Vision, § xii.

CHAPTER XIX.

VISION AIDED BY ART.

§ 138. *Images formed by catoptrical and dioptrical instruments.*

Whether they operate by reflection or by refraction, optical instruments by which vision is aided, serve only to form an image of some external object, which image is to be viewed by the eye, either directly or intermediately.

Any point of an object, seen by reflected or refracted rays, appears somewhere in the direction which the axis of the pencil of rays flowing from the point describes, after its last reflection or refraction. The reason why it does so, is, because the place of its image on the retina is the same as it would be, were the object removed from its proper place into the place of the image, and seen by direct rays. Having no perception of the previous reflections or refractions of the rays at the mirrors or lenses, but only of their action on the retina, we form the same judgment of the apparent place of the object as in the case of direct vision.

1. The circumstances have already been explained, (§ 114), in which the images formed by *reflection*, are of the same size as the object, as is represented in fig. 84; smaller, as in fig. 85 and 86; larger, as in fig. 87; erect, as in fig. 84, 85, and 87; inverted, as in fig. 86; positive, as in fig. 86; virtual, as in fig. 84, 85, and 87.

2. With regard to the images formed by *refraction*, it has already been stated, (§ 45), that if the rays which pass through a lens converge to actual foci, as in fig. 54, the positive image, thus formed, is inverted.

Such an image is smaller than the object, whenever the object is at a greater distance from the lens than twice its

principal focal length; larger, when the object is within this distance.

When an image is formed by any lens, if the rays diverge from a virtual focus, and the object and image subtend equal angles at the centre of the lens, the image is erect. If the lens is a convergent one, the image is magnified.

Divergent lenses always form a virtual and erect image, smaller than the object.

It is a general rule, applicable to all instruments, which form an image to be viewed by the eye, whether the image is formed by reflection or refraction, whether it is smaller or greater than the object, whether it is erect or inverted, and whether it is viewed directly or intermediately, that the apparent magnitude of the object is measured by the visual angle under which it is seen (§ 55), or the angle which the last image of the object subtends at the eye.

§ 139. *Effects of divergent and convergent lenses.*

Let L L′, fig. 95, be a double-concave lens, placed between

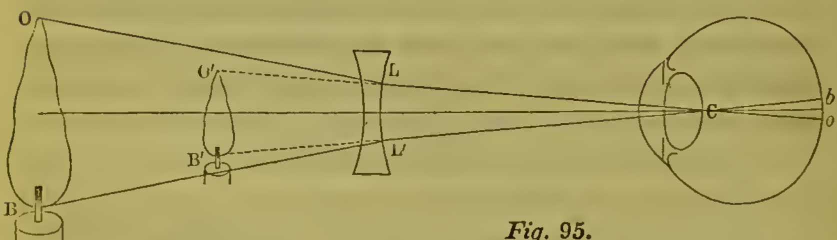

Fig. 95.

the eye and an object, O B; and let O L be a ray of light proceeding from the upper extremity of the object, and B L′ a similar ray proceeding from its lower extremity. The double-concave lens refracts those rays from the perpendicular, so that they fall upon the eye with a less degree of convergency than they would have otherwise done. In the figure, they are made to fall perpendicularly on the cornea. If we continue them towards the retina, they will decussate at C, the focal centre of the eye, and fall on the retina at *o* and *b*. If continued in the opposite direction, as represented by the dotted lines L O′, L′ B′, they will indicate the size of the

diminished, erect and virtual image, O′ B′, which the eye perceives of the object, O B.

Let L L′, fig. 96, be a double-convex lens, placed between

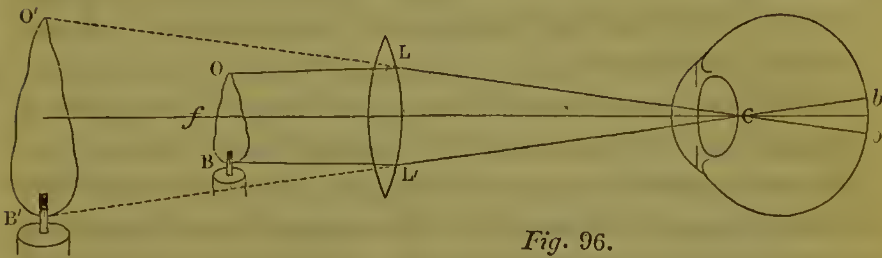

Fig. 96.

the eye and an object O B; and let O L be a ray of light proceeding from the upper extremity of the object, and B L′ a similar ray proceeding from its lower extremity. The double-convex lens refracts those rays towards the perpendicular, so that they fall upon the eye with a greater degree of convergency than they would otherwise have done. In the figure, they are made to fall perpendicularly on the cornea. If we continue them towards the retina, they will decussate at C, the focal centre of the eye, and fall on the retina at *o* and *b*. If continued in the opposite direction, as represented by the dotted lines L O′, L′ B′, they will indicate the size of the magnified, erect, and virtual image, O′ B′, which the eye perceives of the object, O B.

§ 140. *Vision of myopic eyes aided by concave lenses, and that of presbyopic eyes by convex lenses.*

The most frequent, and not the least important, cases, in which vision is aided by art, are those of *myopia* and *presbyopia.*

If the cornea, the crystalline, or both of them are preternaturally convex, they will bring the rays of light too soon to focal points, so that the images of objects, at an ordinary distance, will fall before the retina. The images on the retina, consequently, will be indistinct, and vision confused. To see distinctly, persons having eyes so constructed, bring the object generally to within 5 or 6 inches of their eyes. Hence

they are called *short-sighted.* From the habit of half-closing the eyes, which attends the defect, it is styled *myopia.*

If the cornea, the crystalline, or both of them are preternaturally flat, they will not bring the rays of light soon enough to focal points, so that the images of objects, at an ordinary distance, will fall beyond the retina. Vision, therefore, will be indistinct, as in the case of an object brought too near to a common eye. To see distinctly, persons having eyes so constructed, carry the object to a distance of two or three feet from their eyes. Hence they are termed *long-sighted;* and as the defect generally occurs after the prime of life, it is known by the name of *presbyopia.*

An eye, that has no other defect but that of being myopic or presbyopic, may be assisted by a lens of a proper figure, so as to see distinctly at any given distance.

Suppose C O′, fig. 95, to represent the *greatest* distance of distinct vision to a short-sighted eye; and C O to be the distance at which it is wished that the eye should see an object distinctly. Let L L′ be a divergent lens, as a double-concave, of such a figure, that rays emanating from O will after refraction proceed as if from O′. An object, O B, seen through such a lens, will appear distinct; for the rays, by the diminished convergence, are made to enter the eye in such a direction as permits them to be brought to focal points on the retina, the over-refraction of the myopic eye being compensated by the concave lens.

Suppose C O′, fig. 96, to represent the *nearest* distance of distinct vision to a long-sighted eye, and C O to be the distance at which it is wished that the eye should see an object distinctly. Let L L′ be a convergent lens, as a double-convex, of such a figure, that rays emanating from O will after refraction proceed as if from O′. An object, O B, seen through such a lens, will appear distinct; for the rays, by the increased convergence, are made to enter the eye in such a direction as permits them to be brought to focal points on the retina, the deficient refraction of the presbyopic eye being supplied by the convex lens.

Convex lenses magnify, and concave ones diminish, the

objects that are seen through them. This is not the design, however, with which they are used as spectacles, but merely to alter the course of the rays of light at their entrance into the eye, so as to ensure distinct vision.

§ 141. *Reading glass.*

What is termed a *reading glass* is a double-convex lens, broad enough to permit both eyes to see through it. By spectacles it is proposed only to render objects distinct at a given distance, but the reading glass is used to magnify the object.

The object, such as O B, fig. 96, must always be nearer to the glass than its principal focus *f*, so that the image or magnified object, O′ B′, may be erect, and on the same side with the object. It will appear magnified in the proportion of the angle at C subtended by the image, to the angle at the same point subtended by the object.

§ 142. *Single microscope.*

The nearest limit of distinct vision (§ 84) is about seven or eight inches, and therefore no object, seen distinctly, ever appears to the eye to be nearer than seven or eight inches. An object, much nearer than this, produces a confused image, because the rays being very divergent, cannot be brought to focal points on the retina. Were it not for this circumstance, we should be able to see and distinguish the parts of objects, which are now invisible to us from their minuteness; for when carried very near to the eye, their image on the retina would be so large as to render them visible.

If we bring a pin-hole in a card before the eye, a small object held near the eye, appears much clearer, (fig. 79), because the hole, by permitting only the central or least diverging rays of each pencil to pass, diminishes the magnitude of the circles of dissipation on the retina, and thus ensures a distinct impression. The image on the retina is not enlarged; but, however small the real distance of the object, it seems

removed, when viewed in this manner, to the distance of seven or eight inches, or to be brought within the limits of distinct vision. This affords the only explanation why an object appears magnified, and the only mean by which we can ascertain the degree in which it appears magnified, not only on being viewed through a pin-hole, but when seen through a single microscope. Thus, if the object is really half-an-inch from the eye, and appears as if it were seven inches distant, its diameter will seem enlarged in the same proportion as its distance, that is, fourteen times.

A small convex lens of short focus, or a glass globule, employed for viewing a small object near the eye, is called a *single microscope*. The object being placed in the focus, *f*, fig. 96, of the glass, the divergency of the rays emanating from the object is diminished exactly as in the case of convex spectacles or a reading glass, so that they reach the eye under the same degree of inclination as if they came from an object situated at the ordinary distance of distinct vision.

The lens magnifies the object merely by allowing us to see it nearer. Those lenses, therefore, which from being most convex, have the shortest focus, magnify the most, because they enable us to bring the object nearest to the eye.

The magnifying power of a single microscope is equal to the distance at which we could see the object most distinctly with the naked eye, divided by the focal length of the lens or spherule. If that distance be seven inches, the linear magnifying power of a single microscope of one inch focus will be 7; that of one of $\frac{1}{10}$ inch, 70; that of one of $\frac{1}{100}$ inch, 700. These numbers squared give the number of times that the surface of the object is magnified.

As the small object, viewed through a single microscope, is placed in the principal focus of the lens, the emerging rays will be parallel, and hence the image may be considered as removed to an infinite distance. Its apparent magnitude, therefore, to the eye will remain invariably the same, whatever be the distance between the eye and the lens, and will be equal to its apparent magnitude seen by the naked eye, supposing the eye were placed in the centre of the lens.

The apparent magnitude of an object seen through a convex lens is also invariable, wherever it be placed, when the eye is fixed at the principal focus of a lens by which parallel rays are made to converge to the eye. In this case, the several parts of the object being always seen under the same angles, whatever be their distance, they must consequently appear of the same invariable magnitude.

§ 143. *Compound microscope.*

We have hitherto supposed the object, viewed through a convex lens, to be placed, either between the lens and its principal focus, or in the focus. If it be placed beyond the focus, as in fig. 54, the image is formed on the opposite side of the lens from the object, and is inverted. The positive image, thus formed, will be larger or smaller than the object, according to the distance of the latter behind the principal focus of the lens. (§ 43, 45.)

In the *compound microscope*, and in various other optical instruments, this inverted image is regarded as a new object, and viewed through a second lens. The *object-glass* of the compound microscope is small and very convex, so that its focal distance is very short. The object is placed but a little beyond the focus, so that the inverted image may be formed at a considerable distance, and consequently be much greater than the object itself. This image is viewed through a convex *eye-glass*, and thereby the object appears magnified a second time.

The magnifying effect of the object-glass is found by dividing the distance of the image by the distance of the object; and that of the eye-glass by the rule for single microscopes. These two numbers being multiplied together, give the magnifying power of the compound microscope. Thus, if the first distance be $\frac{24}{10}$ inch, and the second $\frac{1}{10}$ inch, the power of the object-glass will be 24; so that if the power of the eye-glass be 10, the whole power will be 240.

The methods of correcting spherical and chromatic aberration in refracting telescopes, have already (§ 61, 75) demanded

our attention, when treating of the aplanatic and achromatic properties of the eye. The principles, then considered, are applied also in the construction of refracting microscopes, several lenses being combined in the construction both of the object-glass and eye-glass of the best instruments of the present day.

§ 144. *Astronomical telescope.*

The *astronomical telescope* consists of a broad convex object-glass of long focus, by which a bright but minute image of a large distant object is formed in the focus of the lens, and in an inverted position. This image is viewed through a convex eye-glass of short focus, placed at its focal distance from the image. The object appears inverted, and magnified, as in the compound microscope.

Dr Reid remarks, that if a man who had never before seen objects through a telescope, were told, that the instrument, which he is about to use, magnifies the diameter of the object ten times, he might expect to see, instead of a man of six feet in height, a giant of 60 feet. But he sees no such thing. The man appears no more than six feet high, but he appears ten times nearer than he is. The telescope indeed magnifies the image of the man upon the retina ten times in diameter, and must therefore magnify his visible figure in the same proportion, and yet it seems no bigger, but only ten times nearer.

The magnifying power of a telescope depends chiefly, then, on its enabling the eye to inspect a small image, formed by the object-glass, at the distance of seven or eight inches, instead of the large object at a great distance; but to this must be added the enlargement of the image by the eye-glass.

To find the magnifying power of the astronomical telescope, we require to divide the focal length of the object-glass by the focal length of the eye-glass. Thus, if the focal length of the object-glass is 10 feet, and that of the eye-glass 2 inches, the magnifying power will be 60.

§ 145. *Terrestrial telescope.*

For viewing objects in an erect position, a second eye-glass is added to the astronomical telescope, at double its focal distance from the first eye-glass, so that the rays may cross each other, and erect the image. This secondary image is viewed through a third eye-glass. Such is the construction of what is styled the *terrestrial telescope*, or *perspective glass.*

§ 146. *Galilean telescope. Opera-glass.*

The *telescope used by Galileo* shows objects erect; for its object-glass being a double-convex lens, the rays converging to its focus are received on a double concave lens before they reach the focus, which causes them to emerge parallel upon the eye. The rays, therefore, never cross each other before reaching the eye, and hence the object appears erect. The same construction is followed in the *opera-glass.*

§ 147. *Reflecting microscopes and telescopes.*

The magnified image which is to be viewed through the eye-glass of a microscope or telescope, may be formed by a concave mirror. The instrument is then termed a *reflecting microscope* or *telescope.* Such is the microscope of Professor Amici; and such are the Gregorian and Newtonian telescopes.

To enter farther on the construction of these instruments, would be to depart from the physiological object of this work, and encroach within the limits of a subject which belongs to the province of natural philosophy.

CHAPTER XX.

IMPROVABLENESS OF VISION.

§ 148. *Increased sensibility of the retina from remaining long in the dark. Difference between the improved and unimproved eye. Herschel's distinction between the magnifying power of telescopes and their power of penetrating into space.*

NUMEROUS facts might be adduced to show, that the human eye is susceptible of being improved to a surprising extent, especially in the power of discriminating objects by means of feeble degrees of illumination.

Boyle[1] relates the history of a major of a regiment of Charles I. who, forced to seek his fortune abroad, ventured at Madrid to do his king a piece of service of an extraordinary nature and consequence, but which was there judged very irregular. He was therefore committed to an uncommon prison or rather dungeon, having no window to it, but only a hole in the wall, at which the keeper put in provisions, and presently closed it again on the outside, but perhaps not very exactly. For some weeks, this gentleman continued utterly in the dark, and very disconsolate; but by and by he began to think he saw some little glimmering of light. From time to time, this so increased, that he could not only discover the parts of his bed, and such other large objects, but at length, amidst the deep obscurity, could perceive the mice that frequented his chamber to eat the crumbs of bread that fell on the ground, and could discover their motions very well.

It is probable, as Herschel[2] observes, that dilatation of the pupil is not the only cause of seeing better after remaining long in the dark; but that the tranquillity of the retina, which is not disturbed by foreign objects of vision, may render it

fit to receive impressions such as otherwise would have been too faint to be perceived.

Every one has at one time or another experienced, that the imperfect view which we obtain of such objects as are difficult to be seen, from the small degree of light with which they happen to be illuminated, forces us to fix the eye more steadily upon them; but the more exertion we make to ascertain what they are, the greater difficulties does the uneducated eye encounter in accomplishing our object. How great the difference between the improved and the unimproved eye, when both endeavour to mark the place of the moor-game upon the monotonous heath! The experienced sportsman avails himself of the slightest difference of tint, and keeps his eye steadily fixed on it as he advances, while the novice is ever and anon losing sight of his mark, and fretting at his unaccountable want of success.[3]

It is well known, that Herschel never ceased to study the properties of his telescopes, to vary them, and to extend their use. He found that by exercising the eye in a gradual way, it is rendered much more sensible to the impression of weak light, and by this means he was enabled to prosecute his observations of celestial objects much beyond the limits at which other astronomers had been arrested.

He detected[4] two different properties which had not been distinguished; namely, that which consists in augmenting the apparent dimension of bodies, and that of penetrating into the profundity of space to discover objects which otherwise might have been entirely imperceptible. Multiplied examples leave no doubt regarding the truth and striking utility of this distinction. The power of penetrating into space by telescopes is very different from magnifying power, and while it depends chiefly on the quantity of light received by the eye, is assisted in no inconsiderable degree by the increased delicacy of vision acquired by long continuance in the dark.

To common observers, the ring of Saturn always ceased to be perceived when its plane was directed toward the earth; but the feeble light which it reflects in that position was

enough for Herschel, and the ring still remained visible to him.

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[1] Works, iv. 556; London 1744.

[2] Philosophical Transactions for 1800, 53.

[3] Brewster's Treatise on Optics, 299; London 1831.

[4] Op. cit. Éloge historique de Herschel, par Fourier; Mémoires de l' Académie Royale des Sciences pour 1823, p. lxix.; Paris 1827.

ERRATA.

Page 35, line 22, *for* 542, *read* 1,542.
— 122, — 15, — must, — might.
— 219, — 3, — eye-balls, — eye-lids.

THE END.

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